Institute of Sound and Vibration Research

Perspectives on Normal and Near-normal Hearing

B.W. Lawton

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CONTENTS PAGE

ABSTRACT

This literature review sets out the salient features of what is known about hearing threshold measurement, and the documented range of otologically normal hearing and also the expected range of hearing in the general or typical population. By considering the magnitude of expected errors in threshold measurement, it is possible to judge whether, in a particular case of minimal hearing loss, the proffered evidence meets the high standard of proof required in cases of minimal hearing damage.

SUMMARY CONCLUSIONS

Listed below are the major conclusions of this literature review. Page numbers are given so that the reader may refer to individual reviews or chapter conclusions in the main text.

AUDIOMETRIC METHOD

1. Audiometry must be performed using instruments of such stability and accuracy as to ensure that thresholds of hearing determined for an individual will not vary between audiometers, and that results represent an accurate comparison against audiometric zero. (p. 5)

2. Certain procedures must be performed preliminary to audiometry. The ear canal and drum should be inspected visually for obstructing wax or active ear pathology. The patient must be questioned about his most recent exposure to noise, to assess the likelihood of temporary threshold shift being present. Clear instructions must be given, indicating the sounds the patient will hear and the response which must be given. (pp. 7,8,11)

3. Manual audiometry is the method of choice for assessment of occupational deafness claims. Self-recording audiometry is better for industrial monitoring audiometry. (p. 7)

4. Manual audiometry may be performed by an ascending method or a bracketing method. Performed properly, these two methods give equal results. (pp. 12-14,17)

5. Regardless of audiometric method, air-conduction hearing threshold levels should be determined for the frequencies 0.5, 1, 2, 3, 4 and 6 kHz. Failure to test at any of these frequencies is bad practice. (pp. 8,12)

6. A hearing threshold level for 8 kHz may provide additional diagnostic information. (p. 8)

7. Bone-conduction audiometry should be performed by the same method used to obtain the air-conduction results. Use of different methods for air- and bone-conduction audiometry is bad practice. (p. 19)

8. Bone-conduction thresholds are required for each ear, so the hearing of the non-test ear must be masked effectively to ensure that the stimulus tone is heard only in the (intended) test ear. (p. 16)

VARIABILITY OF THRESHOLD MEASUREMENTS

9. Measurements of hearing sensitivity are subject to both systematic and random errors. (p. 21)

10. Systematic or one-way errors in hearing threshold measurement may be attributed to testing conditions and method. (p. 21)

11. Systematic errors in threshold measurements may arise from insufficient attention to audiometer calibration. Instruments should be subjected to periodic calibration against current British or International Standards. (p. 21)

12. Persons involved in hearing testing should be able to produce current calibration documents for their instruments. (p. 21)

13. Ambient noise in the audiometric test space may introduce systematic errors into hearing threshold measurements, always giving artificially elevated hearing threshold levels, particularly at low frequencies. (pp. 40,59)

14. Standards are available which state noise level limits to be satisfied, in relation to the lowest pure-tone levels at various frequencies which may be tested with confidence. (pp. 52,56,59)

15. Air- and bone-conduction hearing threshold measurements must be conducted in a noise-excluding booth or chamber. Hearing threshold determinations performed without the benefit of an audiometric booth are to be viewed with suspicion; bad practice may have resulted in falsely elevated thresholds. (p. 45)

16. If air- or bone-conduction thresholds are inaccurate due to ambient noise, malingering may go undetected. This is careless practice. (pp. 59,75)

17. Temporary threshold shift, resulting from recent exposure to noise, may give misleading and systematically elevated hearing threshold levels. The person being tested should not have been exposed to noise for at least 16 hours before the hearing tests. (pp. 59,60)

18. Unfamiliarity with the process of hearing threshold testing may result in the subject giving misleadingly elevated thresholds. Prudent audiometric practice would be to give the subject a brief 'practice run' at the listening task, and to obtain multiple repeat measurements of the first few frequencies tested, in order to verify that learning effects do not contaminate the final reported hearing threshold levels. (pp. 12,21,60)

19. Random errors in hearing threshold measurements are manifested as different values recorded over a series of repeated tests. (p. 58)

20. The greater part of the random error is usually attributable to judgment variability on the part of the person being tested. (pp. 61-63)

21. No way has been found to predict which subjects will give repeatable thresholds and which will not be able to do so. Repeat testing is the only way to discover which subjects give reliable results. (p. 37)

22. A single determination of hearing threshold level at any frequency must be recognized as only a guess of unknown accuracy. (p. 61)

23. Manual techniques exhibit somewhat larger random error (test-retest variability) than do self-recording or computer-aided audiometric techniques. (pp. 47,48,51,52)

24. The self-recording technique gives hearing threshold levels generally 3 dB more acute than manually determined thresholds on the same ear. (p. 61)

25. Standard deviations of repeated hearing thresholds are smallest (typically 2-3 dB) for the mid-frequencies 1, 2 and 3 kHz. For audiometric frequencies above and below this range, the standard deviation of repeated measurements is larger. (p. 62)

26. Standard deviations of repeated measurements are smallest when the repeats are performed over short intervals, minutes or hours. Longer intervals lead to increased unreliability. (p. 63)

27. Bone-conduction hearing threshold measurements exhibit more variability on repetition than do air-conduction measurements. (pp. 70,72)

28. Audiometer output for bone-conduction testing is calibrated assuming mastoid placement of the bone vibrator. Forehead placement may also be used, but the forehead thresholds determined must be corrected, using standardized values, to 'mimic' mastoid thresholds. (pp. 67,69,78)

29. A conductive hearing loss is said to exist if the bone-conduction thresholds indicate more acute hearing than the air-conduction thresholds. To be a trustworthy indication of conductive hearing loss, the air-bone gap must be 15 dB or larger. (p. 75)

30. If a conductive hearing loss is found to exist, the bone-conduction thresholds are known to give an over-pessimistic estimate of the hearing function of the cochlea behind the conductive blockage. In such cases, the measured bone-conduction

thresholds may be corrected to account for this Carhart Effect, to give a more representative estimate of true cochlear function. (p. 75)

AUDIOMETRIC ZERO

31. Audiometric zero is defined as the modal pure-tone threshold of hearing of otologically normal young people, aged 18 to 30 years. (pp. 77,78)

32. Otological normality is quite simply defined: normal state of health; no obstructing wax in the ear canal; no signs or symptoms of ear disease; and no history of undue noise exposure. (pp. 77,109)

33. A number of national realizations of audiometric zero have been combined to give an international consensus. Specified acoustic outputs over frequency have been defined for a small number of earphone patterns; these specified sound pressure levels are deemed to be the threshold of hearing by air-conduction for young otologically normal ears. (pp. 79,106)

34. A similar effort has been effected to establish the bone-conduction audiometric zero for vibratory input to the skull. (p. 106)

35. For the audiometric frequencies from 500 Hz to 4 kHz, the standardized audiometric zero has been found to be a good representation of the threshold of hearing for young normal ears. Deviations about zero were found to be both positive and negative, with magnitude generally less than 1.5 dB. (pp. 107,108)

36. For 6 kHz, a potentially important frequency for audiological diagnosis, the audiometric zero has been found to be in error by approximately 5 dB. This inaccuracy is in the direction to represent even young, normal ears as having a hearing loss of 5 dB. (p. 108)

OTOLOGICAL NORMALITY

37. The British and International standard definition of otological normality allows considerable scope for interpretation in choosing subjects whose hearing defines audiometric zero. (pp. 87,88)

38. The otologically normal population exhibits a distribution of hearing threshold values for each pure-tone frequency; these distributions are not symmetrical. (pp. 109-111)

39. For the young normal population, the distribution of hearing threshold levels about audiometric zero exhibits slightly larger excursions on the positive side of zero. In other words, the distribution of normal hearing levels is slightly skewed, with the longer tail of the distribution extending to what might be called 'dull hearing'. (pp. 109-111)

40. For the normal population, the dull hearing skewness of the threshold distribution is exhibited for both males and females. The positive skewing is slightly larger for males. (p. 111)

41. For the normal population, positive skewing of hearing thresholds is observed to become more extreme with increasing age for both sexes. (pp. 110,111; Appendix)

42. A small but systematic influence acts in the normal population to skew the hearing threshold distribution towards dull hearing. A likely explanation is undiscovered pathology. (pp. 111,112)

43. A large number of conditions, diseases and activities are known to impair hearing sensitivity although not in all individuals. Few of these hearing risk factors are specified in the British and International standard definition of otological normality. (pp. 112,151-153)

44. Ideally, the definition of otological normality should be made more rigorous, to account for known hearing risk factors. (p. 112)

45. Competent examination of any individual, seemingly normal or obviously hearing-impaired, should be aimed at discovering and assessing the action of hearing risk factors in that individual. (pp. 112,153,154)

46. One group of risk factors applies locally to the ear. These contra-indications of normality include ear or mastoid surgery, any sign or symptom of ear infection, obvious hearing loss (especially fluctuating loss), and persistent tinnitus. (p. 151)

47. A second group of risk factors may be found in the medical history. These contra-indications include genetic factors (deafness among blood relatives), neonatal disease, trauma to the head, use of ototoxic drugs, serious viral infection, balance disorder, and certain diseases of the blood or its circulation. (pp. 151-152)

48. A third group of risk factors is found in a person's activities, recreations or occupation. Some contra-indications are firearms use, close proximity to explosions, noisy leisure pursuits (for example, motor racing or DIY), scuba diving, and exposure to heavy metals or volatile solvents. (pp. 152,153)

49. If any hearing risk factor is found to apply to an individual, that person should not be considered otologically normal (or perfect). (pp. 112,151)

50. The chance of any individual being otologically perfect decreases with age, as hearing risk accumulates. (p. 154)

THE TYPICAL POPULATION

51. The otologically typical population includes members who are normal and members with hearing risk factors or actual hearing loss, but without occupational noise exposure. (pp. 155,156)

52. Data exist which describe the distribution of hearing thresholds of the typical population, for different pure-tone frequencies as a function of age and sex. (pp. 156-161)

53. The typical population exhibits hearing thresholds which are elevated in comparison to the normal subset. The typical thresholds are also more disperse than those for the normal subset. (p. 162)

54. The typical hearing data describe the expected hearing of members of the general population, subject to the action of age, disease and stress of everyday living. (pp. 162,163)

55. Typical hearing data are suggested as a realistic and fair baseline for the evaluation of hearing loss due to noise exposure in an industrial population. Exact specification of the typical population is still under discussion. (p. 163)

PRESBYACUSIS

56. Hearing sensitivity is known to deteriorate naturally with age; the highest frequencies are lost first. This is the most common form of hearing loss in adults. The loss occurs earlier in males than in females, and develops faster. (pp. 179,188; Appendix)

57. Loss of pure-tone sensitivity is given in British and International Standards as a function of age and sex for the "otologically normal population". (pp. 80,110,160; Appendix)

58. Data are available for the typical adult population, giving the loss of pure-tone sensitivity as a function of age and sex. (p. 160; Appendix)

59. Loss of hearing sensitivity, particularly in the higher frequencies, occurs at a faster rate among typical, unscreened adults than among the highly screened, otologically perfect population. (p. 160; Appendix)

60. Regardless of whether an individual is otologically normal or typical, there are no therapeutic measures for presbyacusic hearing loss. (p. 175)

61. Age of onset and rate of onset of presbyacusis cannot be predicted for any individual; once established, it remains as a symmetrical and progressive sensorineural hearing loss. (pp. 165,188)

62. In addition to a loss of pure-tone sensitivity, the normal or typical person must expect some age-related deterioration of speech reception/discrimination ability. (p. 165)

63. Age-related speech-hearing difficulties are first noticed as early as the 40's, with a sharp acceleration of speech-hearing difficulties occurring in the 60's. (p. 188)

64. Age-related speech-hearing difficulties are noticed first in less-than-perfect listening conditions. (pp. 166,181,188)

65. Presbyacusic discrimination loss is thought to be the result of two factors. The cochlea exhibits some loss of hearing sensitivity; the central auditory pathways also suffer some age-related deterioration of form and function. The overall result is speech discrimination loss due to age. (pp. 181,188)

66. Age-related hearing loss occurs in parallel with other hearing pathology, and also in the absence of other hearing pathology. (pp. 160,186)

67. Hearing threshold elevation supposedly due to one cause, noise for instance, should also be assessed in relation to the presbyacusic hearing loss expected for the age and sex of the individual being assessed. If presbyacusis is not taken into account, the hearing assessment must be considered incomplete. (pp. 160,186)

68. Speech discrimination difficulties must not be accepted as direct evidence of hearing damage, without reference to age-related speech difficulties which occur naturally. (pp. 188,194)

ONSET OF IMPAIRMENT OR DISABILITY

69. Hearing impairment is any loss or abnormality of hearing function. Impairment exists within the hearing organ, and is customarily and conveniently measured in terms of elevation of hearing threshold level for pure tones. (pp. 198,199)

70. Hearing disability is a restriction or inability to perform some auditory function in the manner or within the range considered normal. (p. 198)

71. Disability may be the consequence of a hearing impairment, but not an automatic consequence. Minor impairment may produce no discernible loss of ability to perceive everyday sounds. (p. 199)

72. Loss of normal function customarily refers to hearing for speech, so a hearing disability indicates some difficulty with 'everyday' speech reception, and as such should be directly measurable. (p. 199)

73. Speech audiometry, testing in particular the difficult situation of discriminating speech against a background of noise, would seem to be the most direct method for assessment of speech-hearing disability. (pp. 199,231)

74. Speech audiometry is not a standard or standardized practice. Many different materials (test utterances) are used, presented by many different methods. Such diversity is unsuited to the quantitative measurement of hearing disability. (p. 199)

75. Speech-hearing disability is currently assessed by reference to pure-tone hearing thresholds. If sufficient hearing impairment is present, that is, if a 'low fence' threshold value is exceeded, the impairment is deemed to cause a disability. (pp. 212,215,217)

76. Various average thresholds involving different frequencies have been suggested as indicating impairement sufficient to cause speech-hearing disability. Reputable scientific opinion focuses on low fence values in the range 15-30 dB HL averaged over several frequencies (1, 2 and 3 kHz in British practice). (pp. 208,212, 217, 231)

77. Low fence values must be considered in relation to the dispersion of threshold values about audiometric zero. Values less than 15 dB HL imply that a substantial fraction of the otologically normal population is speech-hearing disabled without any known hearing pathology. The deemed-disabled fraction becomes still larger if the typical population is considered. (pp. 217,219)

78. It is plain that no consensus is to be found among the schemes intended to quantify, or even indicate the existence of, hearing disability. (pp. 231,232)

INTRODUCTION

This literature review examines the accuracy and reliability of hearing threshold measurement, with special reference to minimal hearing deficit possibly resulting from occupational noise exposure. In such cases, the various parties involved may be unsure how to proceed if the claimed hearing loss is little different from what is considered to be normal. The problem comes down to this: **Can a minimal hearing loss, showing only a small difference from audiometric zero, be accepted as true considering the wide range of hearing considered to be normal or expected in the general population?**

When a claim is made for noise-induced hearing loss as a result of occupational noise exposure, the complainant is expected to support his claim by an audiological report documenting the present state of his hearing. If the claim involves a small hearing loss, not greatly elevated from normal, a special duty falls upon the otologist or audiologist undertaking the hearing examination. The straight-thinking otologist or audiologist will realize that small hearing losses are of the same order of magnitude as the systematic and random errors known to affect hearing threshold measurements. The straight-thinking otologist or audiologist will realize that it is his professional responsibility to control and minimize the known errors of threshold measurement. Only by eliminating known sources of error will small deviations from zero take on substance and stand without doubt as measured loss.

This review of the literature up to 1990 deals with the errors of hearing threshold measurement, with particular reference to normal or near-normal hearing and the resulting dispersion which may be expected. The concepts of audiometric zero and otological normality receive special attention, as they form the bedrock (not as solid as might be hoped) upon which hearing measurement and diagnosis are based. The expected effect of age is considered from several different aspects. The age-related loss of threshold sensitivity is well known. Much has also been written about age deterioration of speech-hearing ability, which should bear upon the calculation of disability in cases of occupational hearing loss if codification of the relation were to be effected. Limits of normal or expected hearing are examined critically as standards of comparison for the quantification of noise-damaged hearing.

This literature review sets out the salient points of what is known about the methods and errors of hearing threshold measurements. Also examined are the documented range of hearing in otologically normal people, and the range of expected hearing in the general or typical population. By examining the magnitude of expected errors in threshold measurement, it is possible to judge whether, in a particular case of claimed minimal hearing loss, the proffered evidence meets the high standard of proof required to establish the truth of minimal hearing damage.

* * * * * *

Turning now to matters of organization, the contents of this report are drawn exclusively from readings of the works listed in the bibliography, and the reviewer's attempt to assess the state of knowledge up to 1990. Only English-language sources were consulted. This restriction is not as serious as it might seem. Important authors, notably German and Scandinavian, frequently publish in English to reach a wide audience. Important concepts quickly make an appearance in English, as researchers and clinicians attempt to replicate or apply research results.

In dealing with any particular topic, a standard approach has been adopted. A brief introduction is put forward, stating the problem as this reviewer sees it. Individual research papers, conference contributions, book chapters, etc., are then reviewed in chronological order, with an attempt being made to capture the essence of each. After all the reviews have been presented, an attempt is made to summarize the present state of knowledge. Such chapter summaries are a synthesis of the individual reviews, coloured by the opinions and experiences of the reviewer, although every effort has been made to treat each individual report on its own merits.

Considering matters of detail, when a reference in the text is given in majuscules, this indicates a cross-reference to another review, found elsewhere in this report as well as in the list of references. Citations in lower case characters are to works listed in the references alone. Inevitably in works of this sort, a number of technical terms must be used. These terms, which are required for technical accuracy, quickly become tedious in their full enunciations. Therefore, a number of abbreviations will be employed throughout this review; a list is given here.

a-c	:	air-conduction
ANSI	:	Americal National Standards Institute
BAOL	:	British Association of Otolaryngologists
b-c	:	bone-conduction
BS	:	British Standard
BSA	:	British Society of Audiology
BSI	:	British Standards Institution
dB	:	decibel
dB(A)	:	decibel, unit of A-weighted sound pressure level
dB HL	:	decibel hearing level, in relation to audiometric zero
ETFL	:	equivalent threshold force level
ETSPL	:	equivalent threshold sound pressure level
g wt	:	grams weight force
HL	:	hearing level
HSE	:	Health and Safety Executive
HTL	:	hearing threshold level
IEC	:	International Electrotechnical Commission
IHR	:	Institute of Hearing Research (MRC)
ISO	:	International Organization for Standardization
kHz	:	kilohertz, that is, thousands of cycles per second
MRC	:	Medical Research Council
N	:	newton, the unit of force
OAD	:	obscure auditory dysfunction
RETFL	:	reference equivalent threshold force level, viz. the b-c audiometric zero
RETSPL	:	reference equivalent threshold sound pressure level, viz. the a-c audiometric zero

SPL	:	sound pressure level
std.dev.	:	standard deviation
TTS	:	temporary threshold shift
WHO	:	World Health Organization

When such terms as these are necessary for technical accuracy, an effort has been made to give a definition in text, if only by context.

AUDIOMETRIC METHOD

Introduction

The first step in measuring a person's hearing function is the determination of hearing threshold levels, in each ear, for a number of pure tone frequencies. The Hearing Threshold Level is defined as the lowest level of a tone which is heard (and acknowledged) on at least one half of its presentations. Reflection upon this definition will reveal that hearing sensitivity is based upon the technical aspects of the signal presentation and the equally important, but less well controlled, response of the listener.

Throughout the present work, it will be assumed that determinations of hearing threshold levels are performed using an audiometer which fulfils the requirements set out by the International Electrotechnical Commission (1979) and the British Standards Institution (1980). These two Standards specify the characteristics and features of audiometers to ensure:

a) "that tests of hearing, particularly threshold, on a given human ear performed with different audiometers which comply with this standard shall give substantially the same results under comparable conditions;

b) that the results obtained shall represent a good comparison between the hearing of the ear tested and the reference threshold of hearing."

In other words, audiometers shall be of sufficient quality, in the electronic and acoustic sense, to allow repeatable threshold measurements which are accurate in relation to an internationally agreed audiometric zero specifying young, normal hearing.

Taking for granted the use of a precision instrument for the production, control and presentation of audiometric signals at calibrated levels, the problem of hearing measurement now focuses on the relation between tester and subject, mediated through the instrument. The tester must present the test signals, and the subject respond to these signals, in a defined and systematic manner. Over the years, a number of seemingly different measurement schemes, or audiometric methods, have evolved through the efforts of workers in hearing measurement for scientific and medical purposes. These methods have evolved as compromises, offering some degree of precision, while not requiring measurement times so lengthy as to fatigue the listener (introducing variation to the measurement).

Rather than report audiometric methods as devised by their originators, the present review will deal with later versions, as recommended by authoritative bodies. In addition to signal presentation methods, aspects of subject preparation (e.g. instructions, earphone placement) are also mentioned as they bear upon measurement precision.

British and International Standards apply in this country, but only as statements of voluntary consensus; an American Standard has been included, not because it has any force in the United Kingdom, but rather to show the agreement found across national boundaries. Recommendations by professional societies carry special weight for those practitioners claiming allegiance to the particular profession. Several such recommendations are given, to show the efforts being made to regularize and uphold competent practice throughout British audiology. Also included here are recommendations by the Health and Safety Executive, setting out that regulatory body's view of best, prudent audiometric practice (with an undertone of quasi-legal requirement).

It will be noted that authoritative recommendations on audiometric methods first appeared in the late 1970's. Before then, audiometric methods were weighted by the scientific/professional reputations of the originators, even to the extent of being known by the scientist's name. The individual methods have now been adopted by individual authoritative bodies, to be weighted by the power of the body rather than the power of the audiometric method espoused.

The Reviews

HEALTH AND SAFETY EXECUTIVE WORKING GROUP ON AUDIOMETRY (1978)

In its discussion document **Audiometry in Industry**, the HSE stated that the main purpose of industrial audiometry is to monitor quantitatively the hearing status of an individual throughout his or her period of employment, in order to control the risk of occupational hearing loss. This document gives guidance on suitable audiometric techniques, based upon the self-recording method being the technique of choice; the manual method may be used as an alternative.

Self-recording audiometry is a shorthand term for discrete-frequency, pulsed-tone, automatic-recording, air-conduction audiometry performed so that the subject's response to the test signal controls the signal presentation level. This method has a number of advantages. As each subject works to the same simple instructions, audiometrician bias is eliminated. The subject's task involves an unambiguous response which is permanently recorded; the automatic print-out of results, usually in the form of an audiogram, with each response recorded, gives a visible indication of the quality of the subject's test performance. This method of audiometry is sometimes mistakenly called 'automatic audiometry'; this term should not be used. The recording of thresholds is performed automatically by the instrument; the course of the test requires intervention and monitoring by the audiometrician.

Whichever audiometric method is used, self-recording or manual, a number of test preliminaries are recommended. Audiometry is ideally preceded by otoscopic inspection of the ear canals, to detect occlusion by wax or overt pathology of the canal, drum or middle ear. The most recent exposure to loud noise of either occupational or non-occupational nature should be determined by questioning; temporary elevation of threshold will be effectively minimized if the interval between loud noise and audiometric testing is forty-eight hours, although an overnight rest from noise is an acceptable minimum. It is recommended that the test instructions be presented in written form, care being taken to provide a faithful translation for subjects whose first language is not English. If the written form of instructions is not understood completely, verbal instructions should be given. Before fitting the headphones, ear plugs, spectacles, hearing aids, head ornaments, etc., should be removed; the headphones should then be fitted on the subject to ensure proper sealing of the cushions, and to allow the subject reasonable comfort throughout the duration of the test. The subject should be cautioned not to touch the headphones during the test.

The self-recording test begins with pulsed tones presented to the left ear. The recommended order of tone frequencies, in kHz, is: (left) 0.5, 1, 2, 3, 4, 6; (right) 0.5, 1, 2, 3, 4, 6; followed by (left repeat) 0.5, 1, 2, 3, 4, 6. If it is evident that the first two frequencies for the left repeat give results identical to the initial determination, then the repeat series may be terminated; otherwise, the repeat series should be continued as appropriate. During the 30 second period allotted to each test frequency, a record is made of the subject's performance, usually taking the form of a threshold tracing indicating the hearing level associated with each subject response, either 'yes, heard' or 'no, not heard'. Detailed rules are given to determine first if the tracing is valid, and second to evaluate the hearing threshold level from the ascending- and descending-level traces.

If manual audiometry is employed, a rigorous procedure is recommended. The order of frequencies is 1, 2, 3, 4, 6, 0.5, and 1 kHz to be presented first to the left ear, then the right. Additional frequencies, e.g. 8 kHz, may be used as appropriate. A plainly audible signal is presented, at about 40 dB above the subject's threshold; an immediate response should result. Presentations are made at intervals 10 dB quieter until no response is given. At the level last heard, a series of 4 short bursts is made, seeking 2, 3 or 4 'yes' responses. If the tone bursts were heard, the level is reduced by 5 dB, for another series of 4 bursts. The descending thresholds is the lowest level giving 2 or more responses for 4 presentations. From a low level plainly 'not heard', series of 4 tone bursts are given, with level increased by 5 dB for each series until an ascending threshold is indicated by at least 2 bursts acknowledged out of a group of 4. The hearing threshold level to be recorded is the average, rounded to the nearest whole number, of the descending and ascending thresholds determined above.

It might be argued that these HSE recommended methods of audiometry set standards of best, prudent practice for industrial monitoring audiometry throughout Britain. Although not embodied as regulation in the U.K., **Audiometry in Industry** formed the basis for the standards ISO 6189-1983 and BS 6655:1986, describing the recommended procedures appropriate to air-conduction audiometry for hearing conservation purposes.

AMERICAN NATIONAL STANDARDS INSTITUTE (1978)

This American Standard (ANSI S3.21-1978) specifies procedures to be followed in the assessment of an individual's hearing by manual pure-tone audiometry. The Standard applies to both air- and bone-conduction; the possibility is acknowledged that masking might be required.

A number of general requirements are set out for competent audiometry. The external ear canal must be inspected for possible blockage, and recognition of canals which might collapse under the pressure of audiometric earphones. The earphone should be centred over the ear; position of the earphone should be adjusted by the test subject for most comfortable listening or loudest sensation for a 250 Hz tone. The space under the earphone should be free of long hair, spectacle arms or other obstacles.

The instructions should be phrased in language appropriate to the subject, and should note the following points.

1. Indicate that the purpose of the test is to determine the faintest sound which can be heard.
2. The subject must respond whenever the test tone is heard, no matter how faintly.
3. The subject should respond as soon as the tone comes on, and as soon as the tone goes off.
4. Indicate that each ear will be tested separately.

Examples are given of commonly-used responses to indicate 'signal on' and 'signal off': raising and lowering a finger, hand or arm; and pressing and releasing an indicator-light switch. It is recognized that the latency of response varies with signal presentation level. When the tone is clearly audible, the 'on-off' response should be given without hesitation; close to threshold, the response may be hesitant or delayed with respect to the signal.

When testing for air-conduction thresholds, the subject's better ear is tested first with a tone of 1 kHz. Higher frequencies, at octave intervals, and at intermediate frequencies if required, are tested in ascending order. After 8 kHz has been tested, the lower frequencies 0.5 and 0.25 kHz are tested. The initial frequency, 1 kHz, is retested to check the validity of the first threshold, and to indicate the necessity of further retests at higher frequencies.

For each test series, rules are set out to determine a plainly audible starting level for the frequency under test. From the starting presentation which is acknowledged by a positive response, the level is reduced in 10 dB steps until no response is given. The level is increased by 5 dB steps until a 'yes' response is given; the tone is reduced by 10 dB. This sequence of 'softer by 10, louder by 5' is repeated until a threshold is evident from the ascending level presentations. Threshold is defined as the lowest hearing level which produces positive responses for at least half of a series of ascending trials; a minimum of 2 responses for 3 presentations is required to define threshold.

For bone-conduction audiometry, the bone vibrator may be placed on the mastoid or forehead, depending on how the instrument has been calibrated. No advice is given regarding which mastoid should receive the vibrator. The order of test frequencies is similar to that for air-conduction, but restricted to the range 0.25 to 4 kHz. (International Standards on calibration for b-c audiometry, published subsequent to 1978 provide reference levels for frequencies up to 8 kHz.)

The method of recording audiometric results is also specified. A standard audiogram is recommended, with distinct symbols given for different test results determined for each ear.

ANON. (1981)

Procedures are recommended for pure-tone manual audiometry. The procedures, described as accepted by the British Society of Audiology and the British Association of Otolaryngologists, are intended to encourage uniformity throughout British practice.

Two threshold determination methods are described, each built upon a number of basic principles and/or definitions. The threshold of hearing for a pure tone is defined as the lowest level at which the tone is heard for at least half of a limited number of presentations; in practice, this means at least two positive responses for three or four presentations (made by audiometric headphone, bone vibrator or calibrated free-field sound). A tone presentation should be longer than 0.5 seconds; durations of 1 to 3 seconds are recommended, with silent intervals randomly varied. If the signal is heard, a positive response is given by raising the finger, or pressing a button operating an indicator lamp on the audiometer. The response should indicate the entire duration of signal heard by the listener; this following of signal-on-signal-off aids the tester's identification of valid responses, especially very near threshold.

Instructions to the subject are very important in establishing the accuracy and reliability of the thresholds to be determined. A particular wording is recommended:

> "I am now going to test your hearing by measuring the faintest sounds that you can just hear. As soon as you hear a sound, press the switch button (or raise your finger). Keep it pressed (or raised) as long as you hear the sound, no matter which ear you hear it in. Release the button (or lower your finger) as soon as you think you no longer hear the sound. No matter how faint the sound, press the button (or raise your finger) when you think you hear it, and release it (or lower it) when you think you do not hear it."

Alternative wordings are considered acceptable providing the same points of instruction are covered.

The test is performed first in the better-hearing ear, as indicated by the subject. The first tone should be 1 kHz. (This choice of frequency gives the subject every opportunity to perform satisfactorily early in the test: hearing at this frequency is unlikely to be greatly deranged; a 1 kHz tone is easily recognized as artificial, being unlike room noise or bodily noises, including the majority of tinnitus.) After the threshold has been determined at 1 kHz, the test proceeds to 2 kHz, then 4 and 8 kHz, then followed by 0.5 and 0.25 kHz. If needed, intermediate frequencies such as 3 and 6 kHz are tested in their proper place in the sequence. Finally, the threshold at 1 kHz is re-determined as an indicator of learning effects and response validity. The more acute threshold at 1 kHz is accepted; large retest errors indicate the necessity of further retests at higher frequencies.

Alternative audiometric methods are recommended, both based upon signals heard during series of ascending hearing level (or increasing loudness). Both methods start with a presentation of such hearing level as to be plainly audible.

For Method A

1. Reduce the level in 10 dB steps until no response is given.
2. After no response, the signal level is increased in 5 dB steps, until a positive response is given.
3. After a 'yes' response, reduce the level by 10 dB, to begin another ascending series.
4. Repeat the procedure of 'softer by 10, louder by 5' until the threshold becomes evident, that is the lowest level which produces a positive response in at least half of the ascending level presentations.

For Method B

1. Reduce the level in 10 dB steps until no response is given.
2. Confirm that the last level is truly below threshold by giving 2 or 3 further presentations. If no more than one burst is acknowledged, this level deemed to be 'not heard'.
3. Raise the level by 5 dB. Present as many as 4 tone bursts, to expect at least 2 valid responses.

4. If still 'not heard', raise the level by a further 5 dB step, with a further 4 presentations for at least 2 responses. Give further signal level increases until the threshold is established.

It should be noted that both methods determine the hearing threshold by ascending level presentations. Method A requires multiple ascending series, each ending in a positive response. This method has been seen above in AMERICAN NATIONAL STANDARDS INSTITUTE (1978). Method B specifies a single ascent, with multiple presentations at each level, resulting in an acceptable number of positive responses.

Set out in the article are a list of grounds for the choice of basic procedures and audiometric methods.

1. The recommended methods are known to yield thresholds in close agreement with those obtained by most other valid methods. (It must be presumed that Methods A and B yield identical results.)
2. Either test can be performed with reasonable economy of time. (In busy clinical practice, superfluous signal presentations mount up over the testing day, resulting in fewer audiograms per day.)
3. Thresholds are measured with a signal-level step size which reflects the expected variability of the threshold, that is, a 5 dB attenuator step.
4. Either test method can be learned without difficulty, by all grades of testers required to perform audiometry.

These grounds for choice speak for themselves.

INTERNATIONAL ORGANIZATION FOR STANDARDIZATION (1983b)

This International Standard (ISO 6189-1983) lays down requirements and procedures for conducting pure-tone air-conduction audiometry appropriate to monitor the hearing of persons exposed to noise at work. Since hearing conservation concerns normal hearing as well as impaired hearing, requirements are presented for measuring hearing sensitivity down to levels more acute than audiometric zero, that is, to negative hearing levels. Techniques are given for self-recording and manual air-conduction, pure-tone audiometry.

Requirements preliminary to testing are much the same as seen before in AMERICAN NATIONAL STANDARDS INSTITUTE (1978), HEALTH AND SAFETY EXECUTIVE (1978), and ANON. (1981). Otoscopy is required; instructions to the subject are explained; proper placement of the headphones should be achieved.

A slight variation on self-recording audiometry is specified. To start the test, a practice run of 20 to 30 seconds is given; the subject's performance will indicate whether the instructions have been understood. If so, the test is started; both ears are tested by the programme involving a set order of tone frequencies. When both ears have been completed, the subject is given a one minute rest, without disturbing the headphone placement. The first one or two frequencies are retested in the first ear, as a validity check. If the initial and repeat thresholds are in specified agreement, the repeat series may be discontinued. Detailed rules are given to determine if each threshold tracing is valid, and to evaluate the hearing threshold level from the ascending and descending traces; the rules are identical to those given by the HSE.

Two alternative methods are specified for conducting a manual audiometric test: an ascending method; and a bracketing method. Both require an initial familiarization. The first tone, 1 kHz, is presented at a plainly audible level, in order to elicit a prompt positive response. Then, from a minimum presentation level (inaudible), the level is increased until a response is given; this familiarization response estimates the ascending threshold.

For the ascending method, the level is reduced by 10 dB from the familiarization response level. Presentations are made at levels increased by 5 dB until a 'yes' is given; the level is reduced by 10 dB, for another ascending series. This 'louder by 5, softer by 10' sequence is repeated until three responses out of a maximum of five trials occur at a single level; this is the threshold. The next frequency is then tested.

For the bracketing method, the level is increased 5 dB from that for the familiarization. From this audible level, presentations are made at descending 5 dB intervals. When no response is given, an 'overshoot' is made with a further 5 dB reduction. From this inaudible level, presentations are made at increasing 5 dB intervals. When a 'yes' is given, a further 5 dB positive overshoot is made. In all, three ascents and three descents are made. Threshold is determined from the six lowest levels acknowledged as heard, averaged and rounded to an integer value. The next frequency is then tested.

Both methods may be abridged in a specified manner. For the ascending method, testing need continue only until two positive responses have been obtained from three trials. The bracketing method may be shortened by eliminating the 5 dB overshoot intervals specified after a positive or negative response is given during an ascending or descending presentation series. For either full or abridged methods, it should be noted that the ascending method determines threshold from ascending level tone presentation series. For the bracketing method, both ascending and descending series are used to determine threshold. The two methods of manual audiometry have been demonstrated to give identical results, see ARLINGER (1979). Self-recorded thresholds, however, are known to be 3 dB more acute than would be determined by any of the interchangable manual techniques.

(Note: This International Standard, ISO 6189-1983, has also been published as BS 6655:1986.)

BRITISH SOCIETY OF AUDIOLOGY (1985)

This technical note sets out procedures for pure-tone bone-conduction audiometry without masking. The recommendations are intended as an extension to the procedures set out in ANON. (1981). The criterion of threshold test stimuli and subject response methods remain unchanged from the earlier document. Instructions to the subject should be slightly modified, to emphasize that a response should be given whenever a signal is heard, no matter which side.

The bone vibrator should be placed on the mastoid prominence behind the worse-hearing ear, as determined by the average a-c threshold for the frequencies 0.25 to 4 kHz. Hair, spectacles, ear-rings, etc. should be removed from the vicinity of the vibrator; the vibrator must not touch the outer ear during the test.

The order of test is the same as for air conduction, that is, start at 1 kHz, then proceed to successively higher frequencies; after the highest frequency, test 0.5 kHz, then 0.25 kHz. Either Method A or Method B from the 1981 procedures may be used. An important note is offered: without the use of masking, it is not possible to determine without doubt which cochlea (left or right) is responsible for the detection of the bone-conducted signal. In clinical practice, unless the b-c and a-c thresholds are in close agreement, masking must be used to determine the auditory function of each cochlea.

BRITISH SOCIETY OF AUDIOLOGY (1986)

Recommendations are offered on the method for masking in pure-tone audiometry. The intent was to extend the scope of previous recommendations, ANON. (1981) and BRITISH SOCIETY OF AUDIOLOGY (1985) dealing with audiometry by air- and bone-conduction.

Masking is used to prevent the unintended hearing of test signals in the non-test ear, which may happen for either air- or bone-conduction. Three rules are offered, to indicate the requirement for masking.

1. For a-c, masking is needed at any frequency at which the difference between left and right thresholds is 40 dB or more. The worse ear would be the test ear, with masking to be applied to the better, non-test ear.
2. For b-c, masking is needed at any frequency at which the not-masked b-c threshold is more acute than the worse a-c threshold by 10 dB or more. The worse (a-c) ear would be the test ear, with better ear being the masked, non-test ear.
3. For a-c, masking may be needed when Rule 1 is not in force, but when the not-masked b-c threshold is more acute than the worse ear a-c threshold, by 40 dB or more.

Rules 1 and 3 suggest air-conduction thresholds which are considerably elevated from normal and thus need not be of concern in the present review. In the case of rule 2, no abnormal thresholds are supposed, only a small difference between b-c and a-c thresholds. Here, the problem lies in determining whether the worse-hearing ear (by a-c) suffers from conductive blockage. The better-hearing ear (by a-c) is removed from the situation by giving it something to listen to, a masking noise to prevent cross-hearing of the b-c signal applied to the other side of the head. This masking noise should be a narrow band, of one-third or one-half octave bandwidth, with centre frequency equal to that of the test tone. The masker may be applied by audiometric earphone or ear insert phone.

No matter which of the three rules (see above) is in force, the procedure is the same: the masking function is determined, seeking the plateau which indicates the true threshold in the test ear. The apparent tone threshold value, T, is known from the original audiogram; the masker threshold, M, is determined for the non-test ear. The masker is then presented continuously, at a level of M + 10 dB, and the tone threshold is measured again; if the tone threshold increases, some degree of cross-hearing has been in operation. The masking level is increased in further 10 dB steps, until three consecutive increases yield the same tone threshold in the test ear. This final value is the true masked threshold, by air- or bone-conduction as appropriate, for the test ear.

An important principle is offered in the procedures, worth repeating here: **"It is far more important to mask properly at two or three frequencies than to mask incorrectly or hurriedly at all frequencies on an audiogram."**

INTERNATIONAL ORGANIZATION FOR STANDARDIZATION (1989)

This International Standard (ISO 8253-1:1989) specifies requirements and procedures for air- and bone-conduction audiometry. Throughout the standard, it is assumed that all tests will be carried out by, or under the supervision of, a qualified person, that is, someone who has followed an appropriate course of instruction in the theory and practice of audiometric testing.

A number of general conditions and requirements are set out for audiometric testing; most have been seen before in HEALTH AND SAFETY EXECUTIVE (1978), AMERICAN NATIONAL STANDARDS INSTITUTE (1978), ANON. (1981) and INTERNATIONAL ORGANIZATION FOR STANDARDIZATION (1983b).

For manual a-c audiometry without masking, two alternative methods are outlined. These two, the ascending method and bracketing method, are identical to the methods found in ISO (1983b), even to the abridgement techniques specified for each.

If masking is required to avoid the test tone being heard in the non-test ear, a procedure is set out. The wording of the standard would appear to suggest the procedure, rather than require it; experience and clinical judgement take priority over the specified standard method. In any case, the recommended method is what might be called a masking-function-following procedure. Starting from the threshold level for both test tone and masker noise, the masker level is increased by 5 dB. If the tone is now inaudible in the presence of the noise, the tone level is increased to audibility. The noise level is further increased, and the tone tested for audibility. It will be seen that the method follows the masking function by a 'sawtooth' procedure. The masked threshold is determined to be that tone level not made inaudible by further increases of the masker level.

For self-recording or automatic-recording audiometry, a procedure is outlined which is identical to that of the ISO (1983b) standard specifying audiometry for hearing conservation purposes. The assessment of threshold tracings for validity, and the determination of hearing thresholds follow exactly procedures and rules set out by HSE (1978). Procedures are also set out for self-recording audiometry using sweep-frequency stimuli; this Bekesy method is relatively uncommon, being largely supplanted by fixed-frequency self-recording audiometry.

Procedures for bone-conduction audiometry are also set out; masking of the non-test ear is required to ensure accurate measurement of test ear thresholds. Starting from a not-masked b-c threshold determined by either the ascending or bracketing methods (see above), the masking procedure is identical to that for a-c (also see above), that is, the masking-function-following method.

This International Standard has specified audiometric procedures for air- and bone-conduction testing, both with and without masking, with recommended methods for manual and self-recording measurement techniques. These methods form the foundation for clinical practice for both audiologists and otologists, the qualified persons who would bear responsibility for differential diagnosis and/or patient management. Close specification of audiometric methods will most likely be viewed as a severe restriction on clinical practice, an unwelcome intrusion into the domain of professional judgement. The International Standard will not be implemented as a British Standard as it does not conform to British audiometric practice.

Summary

From the recommendations and standards setting out ideal methods of audiometry, it will be seen that no universal method has yet evolved. Manual air-conduction audiometry may be performed by a threshold bracketing method, by multiple ascending-level series and also by a single ascending series of multiple tone presentations. Self-recording audiometry may be performed using a fixed- or swept-frequency test format. Whichever method is chosen for air-conduction, the same should be used for bone-conduction measurements, in order to avoid at least some of the practical difficulties which will most certainly arise if (when) masking is required. One can only hope that these disparate methods will yield thresholds within acceptable (usable) limits of accuracy and precision.

It might be argued that audiometric method, as discussed here, consists of two distinctly different parts, one susceptible to standardization, the other perhaps not. Certain aspects of audiometry are essentially technical matters, or processes of a mechanical nature. This side of audiometry includes earphone pattern, the acoustic output of each standard pattern, and the placement of earphones on the head; presentation order of pure-tone frequencies is, in some cases, built into the programme of the audiometer. Other aspects of audiometric method are not technical matters, but rather deal with the relationship between tester and subject; this side of audiometric method includes such topics as instructions to the subject, signal presentation and acknowledgement, masking method, etc. It is arguable that this second aspect of audiometric practice is basically 'people oriented' and should not be controlled so closely as the technical aspects of audiometry.

It will also be seen from the reviews that two distinct currents exist in threshold measurement practice. At a basic level, monitoring audiometry is undertaken for the purpose of hearing conservation. Such measurements are usually performed in large numbers by audiometricians with only basic training. In such a situation, standardization of practice is useful in order to eliminate audiometrician bias, and to ensure continuity of conditions over long periods of time. At a higher level, in the clinical setting, audiometric method must be subservient to the ultimate end, the diagnosis. Audiometry is used, with the help of the patient, or in spite of the patient, to determine the true state of that person's hearing. It is arguable that, in the last analysis, standard audiometric technique is an irrelevance in clinical practice. Accurate determination of hearing threshold levels is a time-consuming, tedious and tiring process which makes heavy demands upon the intellect of the audiologist and upon the attention of the patient. Part of the demand upon the tester is application of clinical judgment to choose the best technique from all available in the repertoire, in order to obtain the most accurate and trustworthy results from the patient. Any single, standardized audiometric method, to be applied without option to each and every patient, may be seen as the ultimate restriction of clinical judgment, and a denial of professionalism. However, as no single audiometric method has yet emerged as best in all circumstances, the audiologist or otologist may feel thankful for the disparate techniques recommended from many quarters; each audiometric method counselled by an authoritative body provides a potentially useful tool.

THRESHOLD VARIABILITY

All measurements are subject to error. Measurement errors may be systematic or random, or a combination of the two. Systematic error is a repeatable displacement of the measured value from the true (and unknowable) value. In contrast, random error becomes apparent only when repeat measurements are performed; small variations appear as positive and negative differences about the estimated true value.

Hearing threshold levels are measurements, and thus subject to error, possibly systematic, and certainly random. In fact, determination of HTL's is a rather complicated process with a number of opportunities for error to enter the chain. A brief review will point out how or where the measurement process can (and does) go wrong, giving both systematic and random errors in estimating hearing sensitivity.

Audiometric signals are produced and controlled within the audiometer; an instrument which is uncalibrated or mis-calibrated will introduce systematic errors into the hearing threshold measurements. Audiometric earphones may be placed on the wrong ears (systematic) or improperly seated on the ears, making a less-than-efficient acoustic coupling (random). The audiometric method used to determine the HTL will influence the measured value; self-recorded and manually determined thresholds are known to differ in a systematic manner. The state of mind of the listener or subject will, of course, play a primary roll in the quality of the measurements. The subject may be newly learning the audiometric task, in which case the measurements will grow less (randomly) variable over a short span of time, perhaps several minutes. On the other hand, the subject may grow tired or impatient with the task, or lose concentration, with the result that the measurement becomes more (randomly) variable with time. Even the audiometrician may introduce error into the measurement chain; just as the subject will have a criterion to accept a sound as heard, so may audiometricians have a criterion for accepting the patient's signal for 'sound heard'. An audiometrician working on a liberal or loose interpretation of the patient's signals will determine lower (systematically more acute) thresholds of a more variable nature. In contrast, the audiometrician who insists upon the patient's signals being in strict synchrony with the signal onset and offset will record relatively higher (less acute) thresholds which are comparatively stable on repeat.

Air-conduction Variability

What follows are reviews of investigations into individual aspects of the variability of air-conduction threshold measurement. It will be apparent from the introduction above, and from the reviews following, that certain aspects of threshold variability are susceptible to study, while others are not. For example, the placement of earphones (or bone vibrator) is an error source which is easily examined; thresholds are simply repeated with and without replacing the transducer between measurements. In contrast, the subject's listening strategy cannot be strictly controlled or changed; it is arguable that it cannot even be known, only observed.

In the end, there are two great questions to be answered regarding any collection of hearing thresholds determined for an individual. How accurately do the measured HTL's represent this person's deviations from audiometric zero? And, when the thresholds are measured again, how big must the change be in order to be sure that any apparent **worsening** of hearing threshold is, in fact, real?

The Reviews

KYLIN (1960)

As a prelude to laboratory and field studies of temporary threshold shift, the author performed an experiment to determine the test-retest reliability of manual audiometry. Ten normally hearing subjects, aged 20-27 years, each gave ten audiograms over the course of several days. The test results were reported in terms of within-subject standard deviations of hearing threshold levels determined at each audiometric frequency:

frequency, kHz	0.25	0.5	1	2	3	4	6	8
std. dev., dB	2.2	1.4	1.4	1.6	1.7	2.2	2.4	3.1

The values of intra-subject standard deviation show that HTL's are most closely repeatable for the frequencies 0.5 to 3 kHz. Frequencies outside this range show more dispersion for multiple threshold determinations.

ATHERLEY and DINGWALL-FORDYCE (1963)

Tests were carried out to determine the precision of repeated threshold determinations. Twelve male subjects were chosen for negative history of ear, nose and throat pathology, and noise exposure. It was also assumed that, over the course of the study, no subject developed rhinitis, from infection or allergic reaction. Threshold determinations were made at the audiometric frequencies 0.5 to 8 kHz, using a manual bracketing technique based upon 5 dB attenuator steps. Four audiometric tests were performed on each individual, with intervals of one day, one week and one day again.

The data were evaluated to highlight the variability of threshold measurements. Given below are values for the intra-subject standard deviation, in dB, for the four audiograms resulting from each of 24 ears.

frequency, kHz	0.5	1	2	3	4	6	8
std. dev., dB	2.9	2.7	2.6	2.4	4.1	4.4	4.8

It would appear that the overall variation, consisting of the inherent threshold variability and that attributable to repeated earphone placement, is greatest in the higher frequencies, 4 kHz and above.

The data have also been analysed to estimate the smallest change in HTL, from one test to another, which would be considered significant. Given below are such values for the 0.01 significance level, if the change (worsening of threshold) were to be observed in one ear only, and if observed in both ears. A 5 dB attenuator step is implied in these values.

frequency, kHz	0.5	1	2	3	4	6	8
change, dB							
in one ear	12.5	10.0	10.0	10.0	17.5	17.5	17.5
in both ears	7.5	7.5	7.5	7.5	10.0	12.5	12.5

The authors also comment that estimation of the true threshold level is subject to considerable uncertainty. For the 0.01 significance level, the true threshold will lie within the range established by the measured threshold plus or minus the values in dB listed below.

	threshold range, dB						
frequency, kHz	0.5	1	2	3	4	6	8
± error, dB	7	7	7	6	10	11	12

TAYLOR et al (1964)

This paper describes the design, construction and acoustic performance of a mobile booth intended for audiometric testing. A design criterion was stated to be that, within the booth, hearing thresholds as low as -10 dB HL (in relation to British Standard audiometric zero) should be measurable at the frequencies 0.125 to 8 kHz. Maximum permissible octave-band noise levels were derived from Reference Equivalent Threshold Sound Pressure Levels, adjusted to account for bandwidth differences between critical bands and octave bands, and also adjusted to account for the attenuation of a standard earphone and cushion. The derivation assumes local masking only; no acceptable error is specified, so the reader must assume that threshold elevation due to local masking would be less than 0.5 dB from -10 dB HL. The maximum permissible octave levels within the audiometric booth are listed below:

octave band centre frequency, kHz	maximum band level, dB
0.125	12
0.25	6
0.5	8
1	16
2	26
3	29.5
4	28.5
6	30
8	24.5

These maximum band limits give a sum of approximately 36 dB(A) within the audiometric test space. This sound level is given to facilitate comparison with the data of other sources; it does not follow that 36 dB(A) is a criterion of acceptable noise.

HICKLING (1964)

Several studies are described which tested the validity and reliability of manual pure-tone audiometry. Of interest here is a trial carried out, using a bracketing method, to determine the repeatability of thresholds. Four normally-hearing subjects, of unspecified age, were tested repeatedly over the frequency range 0.25 to 12 kHz. Thresholds were obtained three times on a single day, and once each on three consecutive days. No report is made of headphone replacement on the single days series.

The results are reported as average (over subject) standard deviations from the mean at each frequency; maximum deviation between any two readings in the same ear are also given. These results are given below for the same-day and consecutive-days series.

frequency, kHz	0.25	0.5	1	2	3	4	6	8
same day								
std. dev., dB	2.03	2.95	2.02	1.84	2.48	3.49	3.32	3.20
max. dev., dB	5	10	5	5	10	10	10	15
consec. days								
std. dev., dB	3.52	3.64	2.78	2.89	3.18	3.91	4.81	4.04
max. dev., dB	10	10	10	5	10	10	20	15

These results show that variation in threshold determinations is greatest for the higher frequencies, that is 3 kHz and above, for both same-day and different-day threshold determinations. At all frequencies, determination made on different days show considerably more variation than thresholds repeated on the same day. The author offers the suggestion that, for a best estimate of hearing threshold level as might be required in the assessment of a compensation claim, greater reliability can be expected by averaging threshold values within frequency. The mean of values from three audiograms is a reasonable practical compromise.

ATHERLEY (1964a)

A study was undertaken to explore the effect of Temporary Threshold Shift (TTS) upon the hearing threshold levels of young, weaving shed operatives exposed to hazardous noise at work. The hypothesis to be tested was that full recovery from TTS after a weekend away from the noise would be shown by thresholds not differing from those obtained after a longer quiet interval. Put in different words, would a weekend allow full recovery, so that Monday morning's audiogram would be free of TTS from the previous Friday's noise exposure? The answer would, of course, apply only to those individual workers exposed to their own weaving noise.

Seventeen weavers of both sexes, with age ranging from 17 to 35 years, took part in the survey; in all, 31 otologically normal ears were tested. The subjects were drawn from noise environments of two sheds, 3 from one, 14 from the other. The first hearing test was performed on a normal Monday morning for each participant. Manual audiometry was used to determine threshold levels at 0.5, 1, 2, 3, 4, 6 and 8 kHz. The subjects were tested a second time, between one and three months after the first test, but on this occasion after a quiet period of about 16 days. The sub-sample of 3 was tested a third time on a normal Monday after returning to routine working.

The mean hearing levels for each testing occasion are listed below:

frequency, kHz	0.5	1	2	3	4	6	8
first Monday mean of 31 ears, dB	5.7	6.1	12.8	21.6	30.3	15.9	5.4
long break, mean of 31 ears, dB	3.1	6.1	11.8	17.2	23.0	13.0	1.4
second Monday, mean of 6 ears, dB	7.7	8.6	13.4	22.2	29.6	18.0	7.6

The author interpretes these results as indicating that the Monday morning thresholds were elevated from those after the long break, indicating that a weekend did not allow sufficient time to recover from TTS. Such an interpretation is unsound.

The Monday thresholds are, in fact, larger than those after the long break. However, the means for the second Monday were determined using only 6 ears, rather than 31 as for the first Monday. The values for the second Monday are not strictly comparable, and should not have been considered in the author's analysis. However, without the second Monday values, there is now a confounding of variables, in that short break and long break are now indistinguishable from the first and second test with the possibility of learning effects. The experimental design was not of sufficient robustness to answer the original question about the effect of TTS upon hearing thresholds.

BRYAN et al (1965)

It is reported that after removal from moderate levels of ambient noise, normal ears can show improvement in hearing threshold of more than 5 dB in one hour. Such a phenomenon would have considerable effect upon the specification of audiometric zero, the measurement of hearing in individual cases, and estimates of the variation associated with hearing threshold measurements.

Ten normally-hearing subjects gave hearing thresholds over a period of one hour, while seated in an anechoic, quiet chamber. Free-field thresholds were given by the self-recording method, for a 1 kHz continuous tone. Over the testing period of one hour, thresholds were determined at the start of the period, and at 5, 15, 30 and 60 minutes thereafter; between threshold determinations, no sound stimulus was given to the subjects. After 15 minutes in quiet, the mean threshold was 5 dB more acute than the initial determination; after 60 minutes, the difference was 7 dB.

The experiment was repeated with the subjects entering the quiet chamber only for threshold determinations. For this series, with the time between thresholds spent in a normal noise environment, no threshold improvement was observed over the one hour test.

The results of these two test series indicates, to the authors, that relatively low levels of ambient noise, in the range 50-65 dB(A), can result in a significant temporary threshold shift. The threshold recovery shown here, as much as 7 dB, would be an important systematic error in hearing threshold measurement if it were found to obtain for other audiometric frequencies, presented by earphone. In the clinical context however, a relatively long resting period is impractical, trying the patience of subject and audiologist alike.

This experiment was repeated, as given in Steed and Martin (1973), using three pulsed-tone stimuli, 0.25, 1 and 4 kHz. Other relevant conditions were replicated. Although a small recovery of 1.5 dB was observed for the 0.25 kHz stimulus, the second researchers concluded that their work did not support that of BRYAN et al (1965).

HICKLING (1966)

Forty subjects participated in a test-retest study designed to determine the within-subject variance of hearing threshold levels. Males and females, all with negative otological history, were in approximately equal proportions; most subjects were in the age range 17-25 years. All thresholds were obtained by manual audiometry, with the subject seated in a sound-proof booth.

Thresholds were obtained at 1, 2, 6 and 8 kHz, for different testing sequences. During one series of three threshold determinations, the headphones were removed from the subject's head and replaced during the 2 minute interval between determinations. During another series of three HTL determinations, the headphones were not removed during the 2 minute intervals between each determination. The subjects were evenly divided between tests with left ear first and right ear first.

The HTL's were analysed to give within-subject standard deviations for the different testing conditions, and are given below.

frequency, kHz	1	2	6	8
standard deviations, dB				
phones moved				
between measurements	2.27	2.23	3.51	3.40
phones not moved				
between measurements	2.17	2.21	2.39	2.51

From these values, it may be seen that the two higher frequencies are susceptible to variation attributable simply to the action of moving the headphones between threshold determinations. The author attributes this variation to alteration of the high-frequency (shorter wavelength) standing waves established within the ear canal with each individual headphone placement.

The author also lists results from a number of studies of intra-subject variation attributable to test frequency. Representative values of standard deviation are given below by audiometric test frequency.

frequency, kHz	0.25	0.5	1	2	3	4	6	8
std. dev., dB	3.3	3.45	3.28	3.31	3.52	3.87	4.48	4.95

These values are given to support the contention that standing wave variability at higher frequencies contributes to the poorer reliability of the HTL's.

HARBERT and YOUNG (1966)

Detailed analyses were made of fixed-frequency, self-recording audiometric traces for normal and pathological ears. Pure tones of 0.25, 1 and 4 kHz were presented as continuous signals or were pulsed to give 2.5 bursts per second. Signal attenuation rates were 1, 2, 4 and 8 dB per second.

Subjects were tested in a sound-insulated chamber. Seven subjects had normal hearing; nineteen had cochlear lesions. Only one ear per subject was tested using the self-recording method, for the conditions explained above, and by a conventional manual method for comparison.

	attenuation rate, dB/sec	self-recording mean HTL, dB pulsed tone	continuous tone
7 normals	1	10.5	10.5
	2	9.5	10.0
	4	9.0	9.0
manual mean HTL = 12.5 dB HL	8	6.0	6.5
19 pathologicals	1	14.5	20.5
	2	13.5	19.5
	4	12.0	18.0
manual mean HTL = 18.0 dB HL	8	9.5	16.5

Several trends may be seen in these mean results for 1 kHz. Increasing attenuation rate produces lower self-recording HTL's in relation to the manual method HTL. This is seen for both pulsed- and continuous-tone presentations, to both normal and pathological ears. For the normal ears, both pulsed- and continuous-tone presentations lead to self-recording thresholds being more sensitive than those obtained by the manual technique. For the pathological ears, only the pulsed tones repeat this trend. These results may be interpreted to suggest that self-recording audiometry should be performed using pulsed tones. A constant correction factor, to estimate the threshold which would be obtained by a manual technique, could be applied for both normal and pathological ears.

KNIGHT (1966)

A group of young, normally hearing subjects were tested to determine HTL's for one ear, tested by self-recording and manual methods. The methods were used in random order, to determine HTL's at the audiometric frequencies 0.5 to 6 kHz; earphone placement was not altered between the two methods performed on the same specially-modified audiometer.

For the self-recording thresholds, the tone was pulsed to give two bursts per second; the attenuation rate was approximately 5 dB per second. For the manual threshold, only ascending level presentations were made, using 5 dB attenuator steps. To account for the step size, all manual thresholds were adjusted by subtracting 2.5 dB.

The results were reported as the mean of manual (but adjusted) minus self-recorded thresholds, at each frequency for 66 ears. For the values listed below, the adjustment to the manual threshold has been removed, giving the more immediately useful values for raw threshold differences, in dB.

frequency, kHz	0.5	1	2	3	4	6
difference, dB	2.2	3.5	4.0	3.6	3.8	2.4

All these values are positive, indicating that the self-recorded thresholds are the more acute, by approximately 3 dB averaged over all frequencies.

ERBER (1968)

An investigation was performed to determine the effect of age and gender upon the sound pressure produced by an audiometric earphone. The earphone, of a widely available type, was to be placed on the right ear of a number of subjects, and activated by a constant voltage at a number of frequencies. The sound pressure level generated by the phone into each subject's ear was to be measured by a probe-tube microphone, with the tube passed under the earphone cushion.

Sixty individuals were selected for the study. Thirty of these subjects were children, aged 8 to 11 years; the remaining 30 were young adults, aged 20 to 25 years. Both subject groups comprised equal numbers of males and females. The right ear canal of each subject was examined otoscopically for gross abnormality; cerumen content, canal curvature and eardrum state also determined the subject selection.

Three measurement series were performed on each right ear, with the probe-tube microphone and earphone repositioned between each series. The data were reported as mean sound pressure levels observed in the volume enclosed underneath the audiometric earphone and cushion, for each subject group, over a number of test frequencies. Given here are the differences of mean observed SPL for the adults (male minus female) for frequencies most nearly matching those used for audiometric threshold determinations.

frequency, kHz	0.25	0.5	1	2	3.15	4
difference, dB	-1.3	-0.6	-1.5	-1.6	-4.1	-1.4

These values indicate higher levels in the female ears, for a constant earphone excitation voltage. Assuming no actual gender difference in hearing sensitivity, these observed pressure differences would give females slightly more acute thresholds. Similar differences, with similar implications, were found between the adult male ears and children's ears. To the author, these results cast doubt upon the validity of normal threshold data, which at the time of the article were heavily biased to male ears. For present purposes, the adult results given above shed some light upon the known differences between male and female thresholds, for both normal and typical populations. For a known acoustic energy emitted into two enclosed volumes, one larger (male ear), one smaller (female ear), the sound pressure developed in the smaller volume will be higher (and thus more easily heard).

DELANY (1970)

Four otologically normal males, all practised audiometric subjects, gave repeated threshold values in a study designed to estimate the lowest attainable value of threshold variance. Both manual and self-recording methods were used to determine hearing threshold levels at the audiometric frequencies 0.5, 1, 2, 3, 4 and 6 kHz. For each testing session, each subject gave four complete audiograms for each ear. Testing sessions were repeated at irregular intervals covering a total span of 27 months.

The test results indicated that the manual and self-recording methods gave comparable values of variation over the frequency range. The standard deviation associated with repeated threshold determinations assumed its minimum value, 1.7 dB at 1 kHz, and rose to approximately 4.1 dB at 6 kHz. Even with experienced subjects, the first audiometric test on each occasion gave mean hearing levels approximately 1 dB higher (less acute) than second and subsequent tests on that day. This finding could be interpreted as indicating a small amount of re-learning of the task for even experienced subjects.

BESS (1971)

It is known that, in a small percentage of people, the pressure exerted by audiometric headphones upon the external ear can cause the ear canal to collapse or close. If this happens, the air-conduction hearing thresholds measured will be considerably elevated, by as much as 40 dB. This condition may be recognized by (1) inconsistencies between repeated thresholds (as might be observed in cases of malingering or non-organic hearing loss), (2) the existence of an inexplicable air-bone gap, in contrast to the results of tuning fork tests, and (3) discrepancies between the audiometric results and the examiner's subjective impression of the patient's hearing ability in conversation.

From the author's summary from the literature, it would appear that headphone closure of the earcanal occurs mainly in children and in adults aged 50 and over. The author reports two cases of his own, males 55 and 56 years old showing air-conduction thresholds erroneously elevated by 30-35 dB across the frequency range. This condition, if undetected, may lead to the incorrect diagnosis of conductive hearing loss.

BERRY (1973)

The author reviews the problems of ambient noise as a factor in the reliability of audiometric measurements. An outline is given of the laws governing masking of pure tones by noise, particularly critical bands of noise. Attention is given to the difference between local and remote masking, that is, masking by a critical band within its own frequency limits, and at higher or remote frequencies; for the present discussion, remote masking refers to masking which spreads upward in frequency, obscuring a tone outside the limits of the masking band.

For application of the laws of masking to the problem of ambient noise in audiometry, an investigation was undertaken to determine the additivity of two masking bands. Four subjects gave thresholds for an unmasked tone of 1 kHz; thresholds were also determined for the tone masked by one-third octave bands centred at 250 Hz and 500 Hz, used singly and in combination. When the two bands masked in combination, there was "excess masking" not accounted for by simple power summation of the two individual bands.

Using the masking concepts from his review, and the new values of excess masking resulting from his own investigation, the author undertook the calculation of permissible one-third octave band levels in an audiometric test space. For all the conditions dealt with, the criterion of degradation or amount of allowable threshold masking was chosen to be 1 dB.

The sound pressure level, at the entrance to the human earcanal, was estimated to be numerically equal to the Reference Equivalent Threshold Sound Pressure Level measured in the artificial ear required by British Standards. To accommodate a variety of requirements, for measurements of sensitive, young ears or those with higher thresholds, four lower limiting Hearing Levels were considered, -10, -5, 0 and +5 dB HL. Noise band levels were derived so that hearing thresholds at these levels, over frequency, could be determined with a masking error not exceeding +1 dB.

Having estimates of the earcanal sound pressure levels for various lower limiting hearing threshold levels, the masking function could be applied. For the lowest audiometric frequency of interest, 0.125, 0.25 or 0.5 kHz, remote masking would apply. Permissible band levels were calculated to apply for each lowest audiometric frequency, using a conservative estimate of excess masking from multiple low frequency bands (not simply the two bands investigated earlier). For audiometric frequencies other than the lowest, local masking by a single band was held to apply. The resultant bands, from that centred at 0.0315 kHz to that centred at 8 kHz, were finally adjusted by the known attenuation characteristics of a standard audiometric earphone and cushion; this final step limits the applicability to air conduction audiometry using earphones.

In summary, proposed permissible ambient noise levels are given, in terms of one-third octave band limits, for:

1. three lower limiting audiometric frequencies, 0.125, 0.25 and 0.5 kHz;
2. four lower limiting hearing levels, -10, -5, 0 and +5 dB HL; and
3. a single value of maximum permitted threshold elevation, that is +1 dB error.

As an illustration, the limits for the 0.5 kHz, 0 dB HL case are listed in the Table. The band limits listed sum to approximately 51 dB(A). (It does not follow that 51 dB(A) is a criterion of acceptable noise.)

ambient noise levels

one-third octave band centre freq., kHz	band level, dB
0.0315	78
0.04	73
0.05	68
0.063	64
0.08	59
0.1	54
0.125	50
0.160	46
0.2	42
0.25	38
0.315	33
0.4	24
0.5	19
0.63	19
0.8	20
1	21
1.25	23
1.6	26
2	34
2.5	37
3.15	41
4	43
5	40
6.3	37
8	37

ROBINSON et al (1973)

Self-recording audiometry was performed at a British knitwear factory on 147 subjects in various occupations; no subject had previous experience of audiometric testing. Test conditions were varied to examine the effect upon thresholds of the instructions given to the subject and the presentation order of tone frequencies within each audiogram. To test all the conditions in a balanced fashion, each subject attended for audiometry on two occasions, giving two complete audiograms on each visit.

The subjects were split into two groups to test the effect of instructions. One group received only typewritten instructions for each of the four audiograms performed over two visits. The other group had, in addition to the typewritten instructions, a verbal explanation with demonstration of the listening task. No matter in which instruction group a subject was placed, that person did audiometry by two different frequency presentation orders over the course of the experiment. One order was the conventional ascending frequency sequence of self-recording audiometers: 0.5 to 6 kHz, left ear; 0.5 to 6 kHz, right ear. The other presentation order started at 2 kHz, alternately descending and ascending in frequency, with the order so contrived that a change of ear was not accompanied by a change of tone frequency and vice versa. In addition to the effect of instructions and frequency order, it was also possible to examine the effect of learning upon the threshold values, as the experiment involved four audiograms performed over two occasions.

With regard to the instructions, either simple or reinforced, no difference in errors of repeatability or rate of learning could be discerned in the test results. On the other hand, the learning process was facilitated by the modified tone presentation order, enough to recommend alteration from the established test programme of commercially available self-recording audiometers. However, the gain in learning was very slight in relation to the large errors shown by a few subjects.

A learning effect was in evidence for most subjects, taking the form of an improvement in thresholds on each test occasion, compared against the final threshold for each frequency. The very first threshold was on average 7.5 dB high; this error decayed rapidly over the course of the next few thresholds of the test programme. A slight increase of threshold was observed for the initial frequencies of the second visit; the implication was that a small 'de-learning' of the task had occurred between the first and second visits. The authors estimated that 95% of the first measurements were within 10 dB of the final thresholds. When the measurements were repeated (still during the first visit), all measurements were within 10 dB of the final values. The authors commented that the performance of subjects exhibiting large errors at the first test seemed completely unaffected by deliberate attempts to improve threshold reliability. In addition, it was not possible to predict which subjects would give good or bad threshold variability; repeat testing was the only indicator.

ROBINSON and WHITTLE (1973)

An experimental series was undertaken to attempt a systematic determination of the inherent difference between hearing threshold levels measured by self-recording and manual audiometry, each administered under closely controlled conditions to the same sixty-four subjects. The subjects were divided evenly into four groups, according to which method of audiometry was performed first, manual or self-recording, and which ear was tested first, right or left. Complete audiograms for both ears, by both methods, were completed during a single test session.

The same audiometer was used for both methods. Tones were always presented in ascending order from 0.25 to 8 kHz. The manual method used 1 dB intervals for a multiple-presentation bracketing method utilizing positive responses from both ascending and descending level presentations. For the fixed-frequency self-recording method, pulsed tones were used, with the attenuator driven at 5 dB per second. The threshold was taken to be the mid-point of the ascending and descending traces.

The data were analyzed in the form of threshold differences, self-recording minus manual, for all 128 ears tested at each frequency. A systematic pattern emerged in the data; the first mean difference (for 0.5 kHz) was slightly negative, indicating more acute thresholds by the self-recording method, while subsequent differences for higher frequencies were somewhat more negative. The authors concluded, that after elimination of learning effects in the subjects' responses, the difference between hearing levels obtained by the two methods could be taken to be zero for the first frequency tested, and 3 dB for all other frequencies. The lower or more acute thresholds were found for the self-recording method. (This result compares favourably with that of KNIGHT (1966) seen earlier in this section.) The authors also found that successive trials by either method gave lower thresholds; this pointed to the desirability of multiple threshold determination, or some kind of initial training at the listening task.

PELMEAR and HUGHES (1974)

One hundred and eighteen drop-forge workers attended for routine audiometric testing, and were repeat tested at the earliest available opportunity, usually within six weeks. The subjects, within the age range 18 to 65 years, were chosen on the basis of having otologically normal ears, although the criteria are not stated.

Self-recording audiometry was used to test the left ear first, at frequencies from 0.5 to 6 kHz; after the right ear had been tested, left-repeat thresholds were obtained at 0.5 and 1 kHz. The results are reported, for each frequency, as a distribution of signless threshold differences between testing occasions. These data have been re-analysed to indicate a change of threshold at the 0.05 level. Threshold changes larger than the values given below are unlikely to have occurred by chance variation.

frequency, kHz	0.5	1	2	3	4	6
threshold difference, dB	7.0	6.5	4.0	4.5	6.5	8.5

Significant threshold change is likely to be the result of some external factor. Significant improvement might indicate the interference of ambient noise during the first test. Similarly, a significant degradation of the thresholds might indicate noise masking during the second test. Alternatively, a true elevation of HTL might have occurred, as the result of disease or noise exposure.

FEARN (1975)

A number of small studies were performed to investigate different aspects of the learning effect in audiometry. A manual audiometric method was used for each study.

Twenty-four subjects gave thresholds for the frequencies 2, 3, 4, 6 and 8 kHz; manual testing was done on six separate occasions spread over periods up to a year. Mean thresholds are presented for each frequency, for each test occasion. With one minor exception, the first test resulted in higher thresholds, averaged over subjects, than did subsequent tests. After the second test, there was no discernible improvement in mean threshold at any frequency.

A similar trend was illustrated by a series of repeated manual tests performed on two occasions. Eight subjects gave HTL's at the frequencies 0.5 to 8 kHz; a first and second audiogram was obtained on the first visit. On the second visit, another first and second audiogram was obtained. Mean HTL's, averaged over subjects, are presented for each frequency, for each test of each visit. The second test of each visit shows an improvement of about 2.5 dB from the first test.

ROBINSON et al (1975)

Self-recording audiometry was performed on 223 workers at a British airport, with the intention of determining whether accurate measurement of hearing thresholds would best be done at a single visit, or on successive occasions at short intervals. The single visit group provided audiograms of 24 test elements : left and right ears at 6 frequencies each, followed by two repeats of 3 frequencies each for both ears. The other subject group gave thresholds for 6 frequencies in the left ear, followed by 6 frequencies in the right, to end with the initial 3 frequencies repeated in the left; this procedure was repeated on three successive days.

For these industrial subjects, most of whom had some previous experience of audiometry, a learning effect was observed. On average, the very first threshold was 4 dB higher than the final value for that frequency. This difference decayed, over the next few test elements or frequencies, to be within 1 dB of the final threshold. Analysis of the relative magnitudes of within- and between-visit errors lead the authors to the practical conclusion that an extended single test session (with left, right and left-repeat tests) was preferable to a succession of shorter tests on different days.

SHIPTON and ROBINSON (1975)

An investigation was undertaken to provide practical guidance on ambient noise limits suitable for industrial audiometry. The experimental work was based upon the premise that any typical noise spectrum would exert its masking effect upon the lowest audiometric frequency, 0.5 kHz, used in industrial monitoring audiometry.

A number of noise spectra were hypothesized, with shape ranging from gently rising with increasing frequency, to steeply falling with frequency. These hypothetical noise spectra were then adjusted to account for transmission through the walls of a typical single-wall audiometric booth. These adjusted spectra were realized in an anechoic chamber; the shapes ranged from gently falling, to very steeply falling, with increasing frequency. Seventeen subjects gave monaural self-recording thresholds at 0.5, 1 and 2 kHz, in quiet and in the presence of decreasing levels of each of the seven masking spectra. The experimental results were analyzed to give threshold elevation for each test frequency, over the decreasing levels of each masking spectrum; the 0.5 kHz test tone was found to be most affected by masking. The shape of the masking curve was found to be similar for all subjects and all noises; the shape was found to deviate from the commonly accepted form, however.

Drawing on the work of BERRY (1973), the threshold elevation at 0.5 kHz was represented as a function of the level of the external, local masking noise and the hypothetical level of an internal noise (which determines the absolute threshold). The relation between these parameters is given in the form of a chart of elevation from a true threshold, against noise level in the 0.5 kHz band (present in the audiometric booth, assuming the use of a standard earphone and cushion for a-c measurements). The relation is sampled here as noise band limits, listed against elevation from true threshold, all at 0.5 kHz.

sound pressure level in 0.5 kHz band,
giving threshold elevation at that frequency

true threshold, dB HL	threshold elevation, dB 1	2	5	10
-10	4	8	16	24
0	14	18	26	34
+10	24	28	36	44

The authors recommend a threshold elevation criterion of 2 dB, bearing in mind that a significant fraction of people monitored by industrial audiometry may be young normals, which implies a mean HL around zero with some as sensitive as -10 dB HL.

BRYAN (1976)

A brief review is offered of problems which affect the accuracy and reliability of industrial monitoring audiometry. These problems which apply equally to clinical and diagnostic air-conduction audiometry, include:

1. the masking effects of ambient noise upon hearing threshold levels;
2. the repeatability of HTL's;
3. the causes of threshold uncertainty;
4. the difference of HTL's determined by manual and self-recording methods;

5. the elevation of HTL's by temporary threshold shift; and
6. difficulties of differential diagnosis of noise-induced hearing loss.

Each of these topics is dealt with elsewhere in the present paper, as a review of a first-hand research report, and need only be listed here.

The author does report some new information of his own, concerning the minimum threshold shift required to be sure that a deterioration has occurred. Listed below are the minimum shifts which must occur, to be sure (at the 0.05 significance level) that the change is not simply a chance occurrence.

frequency, kHz	0.25	0.5	1	2	4	6	8
threshold shift, dB	17	11	11	14	20	17	20

These values are somewhat larger than results given by other researchers. There is some cause to suspect that the author refers to a signless shift of hearing threshold level, which would encompass a significant improvement of HTL, as well as a significant degradation. Improvement in hearing is possible, indicating successful middle ear surgery or recovery from some temporary pathology; where these two conditions are not applicable, apparent improvement in hearing levels is simply a manifestation of low measurement reliability. Degradation of HTL is the quantity sought in serial audiometry, as an indicator of some potentially sinister process at work, which must be distinguished from chance variation of the HTL.

AMERICAN NATIONAL STANDARDS INSTITUTE (1977)

This American Standard ANSI S3.1-1977 gives maximum sound pressure levels, measured for noise bands within a space used for audiometry, that will produce negligible masking of the test signals. Noise levels are specified such that, for one-ear listening, threshold elevation would be no more than 1 dB re audiometric zero for the frequency under test. Such negligible masking is caused by noise components with frequency close to, or local to, the test signal.

The maximum allowable sound pressure levels are given for noise spectrum levels, and for octave and one-third octave bands centred at audiometric test frequencies. Values are given for open-ear listening (as for b-c audiometry) and for ears covered by an earphone mounted in a specified cushion. The one-third octave band noise levels are presented here, at conventional audiometric frequencies. A noise band level exceeding the permitted limit will compromise the measured threshold only at the frequency indicated, that is, by local masking.

band centre frequency, kHz	maximum band level, dB	
	open ear	covered ear
0.25	13.5	18.0
0.5	9.5	16.5
1	9.0	24.5
2	3.5	29.5
3	3.5	34.0
4	4.0	37.0
6	9.0	36.0
8	15.5	40.0

These maximum noise limits suppose that the level of the masking critical band must not exceed the level of the test tone, at the same place in the earcanal, for each test frequency. The maximum levels listed for each frequency were derived using the following quantities:

1. the Reference Threshold Level (known as the Reference Equivalent Threshold Sound Pressure Level in British Standards) for a specified earphone and cushion, as measured in a standard acoustic coupler;
2. a transformation from measurements performed using the acoustic coupler to corresponding values in the human earcanal;
3. transformation from measurements performed in the earcanal to corresponding values under free-field conditions;
4. a conversion from one-third octave band level to critical band level (an octave band conversion is also given); and
5. attenuation for the specified earphone cushion, if needed.

No indication is given of the variation associated with any of these quantities, either singly or in combination. Nor is there any evidence offered that the calculated noise band limits allow accurate measurement at hearing threshold levels as low as 0 dB HL.

BAKER and WEILER (1977)

A study was conducted, with the expressed aim of investigating possible variations in the HTL's of females during the normal menstrual cycle. Such variations would be in comparison with the HTL's of males, and females using "combination birth control pills". Twelve persons, ranging in age from 18 to 28 years, served as subjects in one of three groups: four women using oral contraceptives; four women not using oral contraceptives; and four men. All subjects reported no hearing abnormalities; the women reported no menstrual abnormalities.

Female subjects gave audiograms twice weekly until the onset of menses had occurred twice. Males were tested for one month, at the same interval. On each occasion, manual audiometry was used to obtain HTL's for each ear for the frequencies 0.5, 1, 2, 4 and 8 kHz. The authors admit to testing different subjects on different audiometers; however, each subject was always tested using the same instrument.

The authors present average HTL's listed by frequency, subject group and quarter of the menstrual cycle (by quarter-month for males). These results are purported to show that the females 'on the pill' had more acute thresholds than the other two subject groups; group differences ranged from 3 to 6 dB. Additionally, the authors found that the thresholds of the normally cycling females exhibited systematic variation within the menstrual cycle, with more acute thresholds observed during the first half of the cycle as compared to the second.

The authors are deceiving themselves, in the opinion of the reviewer. Contrasts between groups of four subjects are simply not worth considering; they indicate only that the experimenters have not properly considered the effects of between- and within-subject variance. Confounding of variables (between audiometers and subjects) was admitted. Audiometry over a single menstrual cycle suggests a minimal effort, not worthy of the expressed aim of the study. One may conclude only that the relationship between hearing threshold level and the menstrual cycle remains an open question.

HEALTH AND SAFETY EXECUTIVE WORKING GROUP ON AUDIOMETRY (1978)

The discussion document **Audiometry in Industry** gives guidance on suitable techniques for industrial audiometry. A description is given of equipment and techniques for measurement of hearing from 0.5 kHz upwards, to levels as low as -10 dB HL. In the section dealing with masking by ambient noise, the use of an audiometric booth is recommended. Ambient noise limits are given in terms of octave band levels within the booth, allowing for attenuation by standard earphones and cushions. The band levels, listed below, allow measurement of hearing down to -10 dB HL, with an error stated to be not greater than 2 dB.

octave band centre frequency, kHz	maximum band level, dB
0.0315	76
0.063	62
0.125	48
0.25	36
0.5	14
1	16
2	29
4	37
8	32

These limits are, in the majority, calculated directly from the remote and local masking band limits given in BERRY (1973), permitting thresholds to be measured down to -10 dB HL with 1 dB error. At 0.5 kHz, the limit listed is a compromise between those given by BERRY (1973) and SHIPTON and ROBINSON (1975). The maximum band limits listed above give a sum of approximately 43 dB(A) within the audiometric booth.

SHIPTON (1978)

Twenty-two subjects, between the ages of 23 and 55 years, participated in an experiment designed to compare the means and dispersions of HTL's determined by two methods of manual audiometry. HTL's were obtained at the audiometric frequencies from 0.5 to 6 kHz, using a minimum attenuator step of 5 dB. The left ear was tested first for each subject. Half the subjects gave thresholds first by an ascending method, and then, without moving the headphones, gave thresholds using a bracketing technique. The other half of the subjects performed the bracketing technique first, followed by the ascending method.

The ascending method started from a pre-determined, but inaudible, presentation level. The signal level was increased in 5 dB steps until a positive response was given by the subject. After that response, the level was reduced by 10 dB and another ascending series was begun. These ascending series were repeated to give a threshold as the lowest level having at least three positive responses, for at least half of the ascending presentations.

The bracketing method also started from a pre-determined, but inaudible, presentation level. The signal level was increased in 5 dB steps until a positive response was given by the subject. After that response, the level was increased a further 5 dB and a descending series begun. The presentation level was reduced in 5 dB steps until the subject gave no response. The signal level was reduced a further 5 dB and another ascending series begun. This sequence was repeated until three ascending and three descending series were completed. The threshold was determined as the mean of the three lowest levels giving positive responses during the ascending series and the three lowest levels resulting in positive responses during the descending series.

From the explanation of the two audiometric methods, it will be seen that the ascending-method threshold is determined using only ascending-level presentations. The bracketing method threshold is the mean of both ascending- and descending-level presentations. The results showed that, over both ears of all subjects, at the six test frequencies, the ascending technique yield HTL's 0.5 dB lower (more acute) than those resulting from the bracketing method. The bracketing method required more time, by several minutes, to complete a full audiogram of six frequencies for two ears.

ERLANDSON et al (1979)

The hearing thresholds of 115 male shipyard workers, aged 25-63 years, were determined by conventional manual audiometry and by swept-frequency self-recording audiometry. Both techniques were performed with the subject seated in a sound-isolated chamber. For the manual method, thresholds were determined using an ascending-level technique for the fixed audiometric frequencies from 0.25 to 8 kHz. For the self-recording technique, subjects responded to interrupted tones presented at 2.5 pulses per second, with 50% duty cycle. The frequency of the pulsed tone was swept from 0.25 to 10 kHz and back to 0.25 kHz; the double sweep required 800 seconds.

The relation between thresholds determined by manual and self-recording techniques was examined by regression analysis of data for each frequency. Values best representing the HTL difference (manual minus self-recording) have been derived from the authors' reported results and are given below:

frequency, kHz	0.5	1	2	3	4	6
difference, dB	-2.4	1.8	2.1	4.6	3.3	4.8

As may be seen from the signs, self-recording audiometry gave more acute thresholds than the manual method for all frequencies save 0.5 kHz.

A threshold reliability study was also performed using 10 subjects, 8 of whom had impaired hearing. Thresholds were determined five times using the self-recording technique. Each subject had been away from loud noise for at least 16 hours with an interval of at least 24 hours between threshold determinations. From the results of this test series, the authors estimated the intra-subject standard deviations, in dB, for both test methods; the values are given below.

within-subject standard deviation, dB

frequency, kHz	0.5	1	2	3	4	6	8
self-recording	3.2	2.4	3.5	2.8	3.3	3.4	4.2
manual	6.3	6.2	4.7	6.6	5.3	7.3	10.4

The authors conclude that the self-recording technique is more reliable than the manual method.

ARLINGER (1979)

Four national laboratories participated in this study to compare hearing threshold levels obtained by the ascending and bracketing methods of pure tone audiometry. The two methods of manual audiometry are fully described in INTERNATIONAL ORGANIZATION FOR STANDARDIZATION (1983 and 1989). Briefly, however, the ascending method presents tones at successively increasing levels until a positive response indicates that the tone was heard; threshold is determined from a number of such series ascending from inaudibility. For the bracketing method, each ascending series is followed by a descending series of tone levels; threshold is determined from responses to three pairs of ascending- and descending-level presentations.

In all, 107 normally-hearing people, age range 18 to 50 years, gave thresholds by manual audiometry using 5 dB attenuator steps. At each participating laboratory, half the subjects had the left ear tested first, half right ear first; similarly, half the subjects were tested using the ascending method first, half bracketing first. Mean thresholds, with standard deviations, are reported by tone frequency for the subjects tested at each national laboratory. These results describe the subjects participating in the survey, and are of no particular interest for present purposes. Differences between methods, in the form of ascending threshold minus bracketing threshold, are given as means over individual ears and tone frequency.

frequency, kHz	0.5	1	2	3	4	6
difference, dB	-0.19	-0.19	-0.29	-0.72	-0.23	-0.26

The negative sign indicates that the bracketing threshold was the less acute of the two determinations. The authors reported that these mean differences were not sufficiently large to indicate any significant difference between thresholds obtained by the bracketing and ascending methods.

HARRIS (1979a)

The author investigated differences in threshold values determined using the standard self-recording method and computer-controlled audiometry. For the self-recording method, the test tone was pulsed at 2.5 pulses per second, 50% duty cycle, with the level changed at 5 dB per second in response to the subject's yes/no response. Threshold was determined as the midpoint of the stimulus tracing controlled by the subject.

The computer-controlled method was intended to present tones and interpret responses in a manner consistent with manual audiometry. After the subject gave a positive response, recognized as such within 1.6 seconds of the signal start, the level was reduced by 10 dB for the next signal presentation. If no response was received, the signal level was increased by 5 dB for the next presentation. Inter-stimulus intervals were randomly varied. This procedure gave ascending level series; when 3 positive responses occurred at a single presentation level, this was taken to be the threshold.

Forty-six industrial workers aged 21 to 63 years, gave thresholds at the frequencies 0.5, 1, 2, 3, 4, 6 and 8 kHz by both methods. The test method administered first was alternated between subjects; the left ear was always tested first. The average threshold (over ears and subjects) is given below for each method.

	mean thresholds, dB HL						
frequency, kHz	0.5	1	2	3	4	6	8
computer-controlled	11.6	8.8	17.0	29.0	33.5	38.4	34.6
self-recording	8.9	6.5	11.8	24.1	30.0	31.7	30.0
difference	2.7	2.3	5.2	4.9	3.5	6.7	4.6

The self-recording method gave more acute thresholds, by an average of 4.3 dB over frequency, than did the computer-controlled method (emulating a manual method). This trend has been noted before, in comparisons of self-recording and manual methods; see KNIGHT (1966) and ROBINSON and WHITTLE (1973).

HARRIS (1979b)

An investigation was undertaken to compare hearing threshold levels determined by self-recording and computer-controlled audiometry with those given by the same subjects tested by manual audiometry. Twelve normal-hearing young people, mean age 23 years, gave full audiograms by each method. Testing order was balanced over the subject sample.

The self-recording and computer-controlled test methods are described in HARRIS (1979a). The manual test was administered by a trained audiologist using the same paradigm employed in the computer-controlled test. Threshold for the manual method was defined as the lowest level giving 2 positive responses for 3 ascending-level presentations.

Mean thresholds are reported for each frequency tested, by each method. All values are given relative to the audiometric zero defined in ANSI (1969), which is equivalent to BS 2497:Part 5:1988.

	mean thresholds, dB HL						
frequency, kHz	0.5	1	2	3	4	6	8
self-recording	-4.2	-5.4	-6.5	-6.7	-6.0	0.0	-1.7
computer	1.5	0.8	0.4	0.2	-0.8	5.4	1.5
manual	-2.1	-1.5	-0.8	-3.7	2.9	1.0	1.3

The mean HTL values for the self-recording and computer-controlled test methods, presage a trend to be seen here later: inaccuracies in standardized values of audiometric zero are such that young, normal ears appear to have a slight loss at 6 kHz. The differences in mean threshold value are listed below:

	threshold differences, dB						
frequency, kHz	0.5	1	2	3	4	6	8
self-recording minus computer	-5.7	-6.2	-6.9	-6.9	-5.2	-5.4	-3.2
computer minus manual	3.5	2.3	1.3	2.9	-3.8	4.4	0.3

The differences in mean thresholds determined by self-recording and computer-controlled audiometry are all negative, indicating that the self-recording method gave more acute thresholds. This trend has been seen several times before. The differences between methods are also relatively stable, indicating a systematic difference between the two methods not requiring the intervention of an audiologist. In contrast, the differences in thresholds by the computer-controlled and manual methods show considerably larger variation. It would seem that the intervention of the audiologist has, in this case at least, introduced random rather than systematic error.

JERIVALL et al (1983)

A study was performed to investigate differences in thresholds obtained by manual audiometry and computer-controlled audiometry, both using the same method and threshold determination criteria. Ten normal-hearing subjects, with age ranging from 19 to 32 years, gave thresholds for both ears, with a frequency sequence of 1, 2, 3, 4, 6, 8, 0.25 and 0.5 kHz with a 1 kHz repeat. For each frequency, the tone presentations began at 40 dB HL. If the subject gave a positive response, which in the case of computer-controlled audiometry would be recognized only within a 0.5 second window from the start of the signal, the signal level was reduced by 10 dB for the next presentation. If the subject gave a no response, the level was increased by 5 dB.

The threshold was defined as the lowest level giving at least three positive responses during a maximum of five ascending presentation series.

A number of audiometric tests were performed by each method, over two testing sessions. The results of interest here are measures of threshold repeatability within method, with headphones removed between determination (performed on different test days). Other results are presented, but confound method, method order, test day and headphone replacement. Listed below are values of standard deviation of thresholds determined by the same method, but on different test days.

	standard deviations, dB							
frequency, kHz	0.25	0.5	1	2	3	4	6	8
computer	3.77	3.43	3.02	3.08	4.17	3.66	3.93	4.29
manual	6.69	5.87	3.43	5.71	3.35	4.73	4.83	5.45

These results show that the test-retest variation is larger for the manual method, particularly at the two lowest frequencies.

INTERNATIONAL ORGANIZATION FOR STANDARDIZATION (1983b)

A section of this International Standard ISO 6189-1983 specifies maximum permissible ambient sound pressure levels within audiometric test rooms. The limits, given in terms of one-third octave band levels, are set to avoid masking, both local and remote, for thresholds measured by earphone at 0.5 kHz and higher frequencies, and for a minimum hearing level of 0 dB in relation to audiometric zero. A criterion of "negligible audiometric error due to masking" is stated; the reader of the standard might interpret this criterion to mean a threshold elevation of less than 0.5 dB HL.

The limits listed in the standard have been drawn from BERRY (1973). The values for 0.5 kHz lower limiting frequency, 0 dB lower limiting hearing level, and 1 dB maximum error (not "negligible error") are listed elsewhere in this review, and need not be given again here.

ROBINSON (1984)

An analysis was made of the configurations of pure-tone audiograms of an otologically screened group of subjects with known noise exposures in a variety of industrial occupations. Before examining the data pool of uncomplicated cases of noise-induced hearing loss in search of typical audiogram shape characteristics, an appraisal was made of the reliability of the individual data.

Right and left ear audiograms, covering the six frequencies from 0.5 to 6 kHz, were available from a number of subjects who had performed serial audiometry at yearly intervals. For 27 subjects, two audiograms were available, and for a further 31 subjects, three were available. Differences were computed between thresholds determined on successive occasions, for each frequency presented to each ear. Listed below are the within-subject standard deviations of the observed differences, and also the maximum signless magnitudes of the differences.

frequency, kHz	0.5	1	2	3	4	6
intra-subject std.dev., dB	4.9	3.9	4.5	4.4	4.5	6.9
maximum difference, dB	23	19	23	21	21	>23

The maximum differences are, of course, extreme values; for individual frequencies, the median threshold change between occasion was 4 dB (without regard to sign) for all frequencies save 6 kHz, for which the median difference was 6 dB. In fact, 95% of all the apparent threshold shifts between occasions were less than 15 dB.

ZWISLOCKI et al (1988)

Advantages and disadvantages are put forward for each of three types of earphones used for audiometric testing. Supra-aural earphones retain the recommendation for this purpose, in preference to circumaural and insert types.

The main strengths of the supra-aural earphone, that type having a cushion which presses against the pinna, are the wide availability of a standardized calibration device, and a reliable calibration method. In practical use, however, this type of earphone gives a somewhat variable threshold for the lower audiometric frequencies, 0.5 kHz and below. This is the result of uncertain, even unstable, coupling between the phone and the ear. Air leaks result in unpredictable sound pressures within the ear-and-phone enclosed volume; repeat placements may give a better or worse seal, leading to a different apparent threshold.

In the supra-aural phone, wave effects become important at frequencies above 2 kHz. When the signal wavelength becomes short, the size and shape of the enclosed volume influence the sound pressure occurring at any point. Positioning of the earphone over the pinna and ear canal can also affect the measured threshold. In spite of these drawbacks, the supra-aural earphone is still recommended for audiometric use.

ARLINGER and KINNEFORS (1989)

Insert earphones, coupled to the ear by means of a long plastic tube and foam ear plug, are being used for a number of audiometric applications as an alternative to any of the standard patterns of supra-aural earphone. One seemingly attractive use of the insert phone would be in the determination of pure-tone thresholds; the insert phone should be free of certain leakage and acoustic coupling factors which cause variation in thresholds determined using standard supra-aural earphones.

A study was performed, determining the hearing thresholds of 18 young, otologically normal listeners (36 ears) using both insert and standard phones. The mean thresholds for each transducer type are of little interest here; however, the standard deviations over frequency are applicable to the problem of threshold variability. This statistic is given below, for thresholds determined using each transducer. Caution must be exercised here: the values of standard deviation given below contain variation between individual ears and variation attributable to the different patterns of phones. Any difference may be ascribed to <u>extra</u> variation associated with one pattern.

standard deviations, dB,
of hearing thresholds for 36 ears

frequency, kHz	0.25	0.5	1	2	3	4	6	8
by earphone	3.8	3.5	3.7	3.5	3.7	4.2	5.2	5.2
by insert	4.7	3.2	4.2	4.0	4.2	5.6	5.2	4.9

Overall, the supra-aural earphone has a slightly smaller standard deviation. The insert phone is seen to produce more variable threshold measurements, in spite of its possibly improved acoustic coupling to the earcanal.

INTERNATIONAL ORGANIZATION FOR STANDARDIZATION (1989)

A portion of this International Standard ISO 8253-1:1989 deals with the level of ambient noise which must not be exceeded in an audiometric test room if masking of the test signal is to be avoided. Values are given as one-third octave band levels, for all bands from 0.0315 to 8 kHz. The specified band levels would allow measurement of hearing thresholds as low as 0 dB HL, with a maximum uncertainty of +2 dB.

Noise occurring in the low frequency bands will cause masking of threshold signals presented at higher frequencies. Consideration of this upward spread of masking, or remote masking, means that the low frequency noise level will determine the range of audiometric frequencies for which thresholds may be determined accurately. Noise limits specified in this Standard permit threshold measurements from alternative lower limiting frequencies of 0.125, 0.25 or 0.5 kHz; the maximum audiometric frequency is 8 kHz in each case. Given in the Table below are the noise limits associated with the test frequency range 0.25 to 8 kHz, for bone- and air-conduction tests, with open and covered ears respectively. The noise limits for lower frequency bands are set to avoid remote masking of the lowest audiometric test frequency, 0.25 kHz; for noise bands within the audiometric test range, the limits are specified to avoid local masking of the audiometric tones. A noise band level exceeding the stated limit will compromise threshold measurement over the stated frequency range, or to the stated limit of uncertainty.

Consideration of the noise limits for b-c and a-c tests, for open and covered ears respectively, reveals that the difference between values listed for each frequency is not identical to the earphone-cushion attenuation, as would be expected. It would appear that the noise limits have been derived from (unknown) sources which give different data for the same phenomenon. This internal inconsistency renders the International Standard equivocal on the subject of ambient noise limits for audiometry.

one-third octave band centre freq., kHz	maximum band level, dB	
	b-c test	a-c test
0.0315	63	66
0.04	56	62
0.05	49	57
0.063	44	52
0.08	39	48
0.1	35	43
0.125	28	39
0.16	21	30
0.2	15	20
0.25	13	19
0.315	11	18
0.4	9	18
0.5	8	18
0.63	8	18
0.8	7	20
1	7	23
2	7	25
1.6	8	27
2	8	30
2.5	6	32
3.15	4	34
4	2	36
5	4	35
6.3	9	34
8	15	33

LUTMAN et al (1989)

Serial monitoring of hearing is most commonly performed as part of an industrial hearing conservation programme, with the objective of identifying shifts in hearing thresholds which may be attributable to noise damage. Implicit in this objective is the requirement that a shift in threshold should be detected at the earliest opportunity, when the magnitude of the shift is at its smallest. In the industrial context, serial monitoring audiometry is most commonly performed by the self-recording method; manual methods are used, but not to the same extent.

The authors describe a study conducted as an extension to the MRC/IHR National Study of Hearing. The objective was to compare hearing thresholds determined by the self-recording and manual methods, conducted serially on the same subjects. The self-recording audiometry was computer-controlled, even to the stage of 'reading the traces' with a minimum of intervention by the audiometrician. The manual audiometry was performed by the method set out in ANON. (1981), said to be recommended by the BSA and BAOL. Using these two methods, manual and self-recorded thresholds were obtained at the frequencies 0.5, 1, 2 and 4 kHz, for 120 persons (240 ears) aged between 40 and 65 years. Repeat thresholds were obtained 2 to 3 years later, again using both methods.

For each ear tested, differences between second and first threshold were calculated. Mean differences are presented below for each audiometric method; also given are the standard deviations and ranges of threshold differences. Positive values indicate a worsening of threshold.

	second threshold minus first threshold, dB			
frequency, kHz	0.5	1	2	4
manual method				
mean	2.24	2.10	1.48	-0.51
std. dev.	6.9	4.8	5.0	7.1
range	-21,+39	-10,+20	-14,+16	-20,+21
self-rec. method				
mean	0.20	-1.34	-0.14	0.65
std. dev.	7.2	6.9	6.6	7.2
range	-27,+32	-30,+21	-29,+22	-33,+24

The range values reported should provide a stark warning to audiologists and audiometricians: repeat thresholds may vary greatly from the original determinations, by as much as -33 dB and +39 dB. These differences are associated with an inter-test interval of 2 to 3 years; one might hope that shorter intervals, on the order of days or even minutes, would yield smaller inter-test ranges.

Turning to the standard deviations associated with each audiometric method, it may be seen that the variation is generally smaller for repeat thresholds performed by the manual method. Over all frequencies pooled, the authors give standard deviations of 6.1 and 7.0 dB for the manual and self-recording methods, respectively. Although small, the authors feel this contrast is worth noting.

The authors also contrast the mean threshold differences for the two methods. For the self-recording method, the threshold differences are both relatively small, and distributed about zero; the inference is that no change of hearing threshold occurred over the 2 or 3 years between tests. For the manual method, the conclusion is different. It would appear that, for the same ears, thresholds became worse at the lower frequencies tested. As the authors themselves remarked, such an occurrence is unlikely to be true; it is more likely that the manual results contain an element of audiometrician bias. "The nature of the bias is at present unclear, but may relate to an unconscious reluctance of audiology staff to record apparent improvements in hearing." This also should be a warning: audiometricians should not carry out tests with previous results open in front of them.

Conclusions on Air-conduction Threshold Variability

As anticipated at the beginning of this chapter, errors in the determination of air-conduction thresholds have been shown to be both random and systematic. Random variability is manifested as slightly different values obtained on each occasion in a series of measurements; these random errors are both positive and negative deviations from a measure of central tendency. On the other hand, systematic errors appear as a uniform displacement. It may have become apparent, through the reviews presented here, that in the case of hearing threshold determination, systematic errors usually work to **elevate** the threshold, to make the hearing appear less acute than it really is.

One important source of systematic variability in threshold measurement is the effect of background noise. Ambient noise in a space used for audiometry will, at very modest levels, mask the perception of audiometric signals, producing apparently elevated HTL's. Such ambient noise need not be closely matched in frequency to the audiometric signal, but may mask remotely, that is, the noise may affect an audiometric signal of a quite different frequency, usually higher. In the reviews presented here, permissible limits for background noise were taken from British and International Standards; values are listed for a-c testing (with some noise attenuation provided by the audiometric earphone) and for b-c testing (with the ear uncovered). For present purposes, viz. the accurate measurement of normal hearing sensitivity, care must be taken to avoid the disturbance of very acute hearing by masking noise. Noise levels must be sufficiently low to permit the measurement of HTL's as low as -10 dB HL, which might be considered the practical lower limit of normal hearing. In the Standards and reports reviewed here, alternative noise levels are given which would allow accurate measurement of thresholds only as low as 0 dB HL, or even +10 dB HL. These alternative permitted noise levels must be recognized for what they are: admissions of systematic error deemed acceptable for certain audiometric applications. The higher permitted noise levels represent a pernicious compromise, an admission that large errors, possibly as much as 20 dB, are acceptable in the measurement of normal hearing.

Another systematic elevation of threshold may occur if the subject or listener has recently been exposed to intense noise. The person may be suffering a temporary dullness of hearing, known as Temporary Threshold Shift. Although not well represented in the literature on threshold variability, TTS is a well-researched phenomenon in its own right, as a sub-topic of noise-induced hearing loss. There exist reasonably well understood relations between frequency content and duration of the fatiguing sound, and the level of, and recovery from TTS. The phenomenon is sufficiently well known to be taken account of in competent audiometric practice; during the preparations for hearing testing, the subject should be asked when he or she was last exposed to noise. In industrial monitoring audiometry, an interval of 12 to 16 hours is considered sufficient for TTS to decay, so that the thresholds will be measured at their true values.

Just as the effect of TTS is transitory, so is the effect of learning. In the reviews here, several researchers have noted that, for the first few frequencies tested, subjects gave thresholds less acute than when retested a few minutes later. This is learning, growing familiar with the stimuli and the listening task; it takes the form of a threshold elevation, a systematic error, which decays as the subject grows confident with the listening task. This transitory error is accounted for in the audiometric methods of the previous chapter. In manual audiometry, the first tone is specified to be 1 kHz, an easily recognizable tone quite different from any room noise and unlikely to be confused with bodily sounds. The subject learns the task with this plainly artificial stimulus, then proceeds to other audiometric frequencies. At the end of the test, the 1 kHz threshold is repeated. If the difference between first and repeat determination is 10 dB or more, the more acute threshold is accepted (the difference is attributed to learning). Thresholds are repeated for the other audiometric frequencies, in their turn, until the difference between initial and repeat threshold is 5 dB or less; when this condition is satisfied, learning of the listening task is deemed to be complete. For self-recording audiometry, a similar approach may be adopted, with repeats of the first few frequencies (usually lower tones) until the initial and repeat thresholds agree. Alternatively a practice period may be given, during which no data is recorded. In any case, gross learning effects in the audiometric process will be relatively short-lived, probably complete in only a minute or two, by which time the subject is confident in the task and giving good thresholds.

Discussion of audiometric method turns the attention to the last source of systematic threshold variability represented in the reviews here. Thresholds obtained by the self-recording method are known to differ systematically from values obtained by a number of the manual methods. The differences between method should not be thought of as 'error'; this term is too heavy with sinister implications. In this situation, 'predictable displacement' would be more appropriate. Several of the investigations reviewed here have dealt specifically with this displacement; the results are gathered here for comparison.

	threshold difference, dB manual minus self-recording							
frequency, kHz	0.25	0.5	1	2	3	4	6	8
KNIGHT (1966)	-	2.2	3.5	4.0	3.6	3.8	2.4	-
ERLANDSON et al (1979)	-	-2.4	1.8	2.1	4.6	3.3	4.8	-
HARRIS (1979a)	-	2.7	2.3	5.2	4.9	3.5	6.7	4.6

From the values in the table, it may be seen that the difference in thresholds is generally between 2 and 4 dB, with the self-recording method giving the more acute values. This situation is cleanly resolved by ROBINSON and WHITTLE (1973), who suggest a 0 dB method correction for the first frequency tested (to account for learning), and 3 dB thereafter. The practicing audiometrician can simplify this correction even further by first obtaining a superfluous threshold at an unwanted frequency, thereafter, the 3 dB correction would apply.

Attention must now turn to the consideration of random errors in determination of HTL's. Such errors may be seen as relatively small fluctuations in the threshold values observed in a series of measurements obtained from the same subject. If only one determination is made, the audiometrician must be prepared to admit that the measured value is only a guess at the true threshold, which will probably lie within a certain hearing level range about the observed value. A number of research reports seen here have addressed the width of this uncertainty range, which is encapsulated in the intra-subject or within-subject standard deviation. This quantity may be estimated from repeated threshold determinations; it will include any variability inherent in the subject, e.g. listening strategy, fatigue, etc., with some influence from external variables such as replacement of the headphones between threshold measurements. A number of estimates of within-subject standard deviation are drawn together from the reviews, and presented in the table here.

within-subject standard deviations, dB

frequency, kHz	0.25	0.5	1	2	3	4	6	8
KYLIN (1960)	2.2	1.4	1.4	1.6	1.7	2.2	2.4	3.1
ATHERLEY et al (1963)	-	2.9	2.7	2.6	2.4	4.1	4.4	4.8
HICKLING (1964)	3.5	3.6	2.8	2.9	3.2	3.9	4.8	4.0
HICKLING (1966)	-	-	2.3	2.2	-	-	3.5	3.4
ERLANDSON et al (1979)	-	3.2	2.4	3.5	2.8	3.3	3.4	4.2

These determinations of intra-subject variability show a surprising consistency among the various reporters, so much so that a general trend is discernible over each row of values. It appears that thresholds are more variable for the extreme frequencies, 0.25, 0.5, 6 and 8 kHz; the important mid-frequencies 1,2 and 3 kHz are the less variable.

On the basis of such estimates of intra-subject threshold variability, a few researchers have gone one step further, to estimate the smallest change of threshold which may be deemed trustworthy. The magnitude of such significant change depends, of course, upon the risk one is willing to accept of placing trust in an apparently changed threshold value which is truly a chance variation. Significance levels are commonly 0.05 and 0.01, indicating the risk of failing to identify an untrue hypothesis.

smallest trustworthy change, dB

frequency, kHz	0.25	0.5	1	2	3	4	6	8
ATHERLEY et al (1963)	-	12.5	10.0	10.0	10.0	17.5	17.5	17.5
PELMEAR et al (1974)	-	7.0	6.5	4.0	4.5	6.5	8.5	-
BRYAN (1976)	17	11	11	14	-	20	17	20

The values of the smallest trustworthy change reflect the trends seen above, in the within-subject standard deviations. For the more extreme frequencies, a relatively larger change of threshold must be observed to be accepted as true, in comparison to the smaller values needed in the mid-frequencies. Such trustworthy changes are usually thought of as elevations or worsenings of thresholds, as might be expected from the action of some pathological agent, be it infection, noise, ototoxic drug or whatever. The other side of the coin must not be ignored, however; trustworthy improvements of hearing thresholds may be sought after ear surgery, tinnitus therapy, etc.

As a final comment on within-subject variability of hearing thresholds, it is worthwhile to consider values of the largest changes measured over a series of audiograms. From the research reviewed here, two sets of values are reported.

largest observed threshold change, dB

frequency, kHz	0.25	0.5	1	2	3	4	6	8
HICKLING (1964)	10	10	10	5	10	10	20	15
LUTMAN et al (1989)	-	39	30	29	-	33	-	-

The values of HICKLING (1964) show the largest difference of threshold measured in any one of his experimental subjects over consecutive testing days. One must be able to assume that the experimental subjects were reasonably practised at their listening task, having given a number of audiograms over several testing days. The subjects employed by LUTMAN et al (1989) are at the other end of any training/familiarity scale. Their subjects were members of the general population, giving audiograms separated by intervals of 2-3 years. The values of maximum observed threshold difference are very large, shockingly large, but are best brought out in the open, as a reminder to the audiological community that the hearing threshold level is a measurement prone to error.

Bone-conduction Variability

Up to this point in the discussion, all aspects of audiometric variability have been addressed from the standpoint of air-conduction measurements. This view of the problem has been taken for convenience only; most sources of threshold variability will also be at work in the bone-conduction situation. There are, however, a few conditions which apply only to bone-conduction testing, and have the effect of making b-c measurements subject to an additional number of systematic and random errors.

Generally speaking, b-c measurements are not sufficiently trustworthy to stand alone; these data always accompany a-c thresholds, in a supporting role. When hearing is normal or near-normal, as assumed for the present review, b-c thresholds are of little use, adding only an inexact confirmation of the conclusion reached upon the basis of the a-c measurements. If some conductive pathology exists, b-c measurements give only an indication of its magnitude. The reviews which follow will illustrate why b-c measurements are held in such low regard.

The Reviews

CARHART (1950)

The author discusses the contribution to diagnosis which bone-conduction audiometry can make, if steps are taken to ensure proper test methodology. Adequate b-c testing has four requirements.

1. The class of hearing to be tested will determine the acoustic environment needed. If one wishes accurate thresholds from normal or near-normal subjects, a soundproof testing chamber is required. If such an environment is not available, it is still possible to obtain useful measurements on hard-of-hearing subjects, for whom modest levels of room noise will be inaudible.

2. The second requirement is that the instrument shall be of an approved type and functioning satisfactorily. (At the time of

writing, standards for bone vibrators and their output levels were non-existent. A simple calibration procedure is outlined for frequencies over the range 256 to 4096 Hz, using about 10 young, normal hearing adults and a similar number of pure, cochlear loss cases. A correction factor would result, to be applied to b-c readings obtained on that instrument alone.)

3. An effective system is required for controlled masking of the opposite, or non-test, ear. This ensures that responses relate only to signals heard in the test ear.

4. Last, the tester or audiometrician must be well trained and have good insight for details of the hearing loss which emerge during test.

It should be noted that these requirements are as valid today as when first written. Progress has brought instruments which can deliver dependable test and masking signals, over a wide range of frequency and level. The other requirements remain, however.

Whenever adequate b-c audiometry is available, results can be obtained which are useful in differential diagnosis. The author presents several case reports of b-c audiograms taken before fenestration surgery for otosclerosis. After surgery, the b-c hearing levels are seen to become more acute by about 5, 10 15 and 5 dB at 512, 1024, 2048 and 4096 Hz, respectively; 500, 1000, 2000 and 4000 Hz would be the modern values. The author interprets this phenomenon, now known as the 'Carhart Effect', as a systematic error in b-c measurements due to a mechanical blockage of signal transmission paths by the otosclerotic disease process. When the middle ear is functioning normally, b-c vibration will radiate into the external ear canal and also into the middle ear, to be transported by these routes to the inner ear, there to be combined with that portion of the stimulus arriving directly by bone vibration. When there is a middle ear defect, the total amount of vibrational energy reaching the inner ear is obviously reduced. If the middle ear defect is lessened or corrected, the b-c threshold will **appear to improve**, due to the 'clearing' of the indirect paths for acoustic energy.

HART and NAUNTON (1961)

The authors were of the opinion that clinical bone-conduction audiometry should be performed with the vibrator placed on the forehead. To further the acceptance of this test method, the authors carried out repeated bone-conduction tests, with the vibrator on the forehead and on the mastoid. Using four subjects, five thresholds were determined for each test frequency, for each vibrator placement.

From their test results, the authors concluded that the forehead placement gives better b-c threshold reliability. Variations about mean threshold, for each subject, were relatively small, less than 2 dB, for the forehead placement; variation did not fluctuate with frequency. On the other hand, variations about mean threshold by mastoid vibration ranged from 4 to 6 dB. The authors suggested that the frontal bone should be the site of choice for clinical b-c tests.

It should be pointed out that British and International Standards from the time that this report was published, up to the present day, all specify vibratory inputs appropriate to mastoid placement of the bone vibrator. Frontal placement of the vibrator has not been adopted.

WHITTLE (1965)

The author reviews in some detail the difficulties associated with the measurement of hearing by bone conduction. A measurement procedure is described, and the results of a new threshold determination are presented in relation to the British Standard current at the time of writing.

In any measurement of hearing thresholds by bone conduction in normally hearing subjects, there exist a number of physical and subjective factors which can influence the accuracy and precision of the threshold measurements. The first of these is attenuation across the head. When a vibratory stimulus is applied to a point on the head, the whole skull is set in motion. There may be some difference in the magnitude of vibration occurring at the right and left cochleae, due to placement of the bone vibrator on one mastoid. In practice, however, it is virtually impossible to stimulate a single cochlea by bone-vibration.

The impossibility of monaural vibratory stimulation leads to the second factor affecting threshold measurements: masking the non-test ear by air-conduction. Broad-band noise has the disadvantage that most of the acoustic energy is ineffective in masking the test tone; in addition, different overall levels are required for each different test tone. Narrow-band noise, typically a one-third octave band, is the preferred masking stimulus. The one-third octave band is a standard acoustic bandwidth, which most nearly matches the critical band of the ear, over most of the frequency range of human hearing. Thus, a critical bandwidth of noise, centred about the frequency of the test tone, completely engages the relevant frequency analysis capabilities of non-test ear, without presenting ineffective (out-of-band) energy which results in a higher-than-necessary masking stimulus. This concern for minimum masking levels is relevant to cross-hearing of the masker, in this case, air-conduction noise presented at such a high level that bone vibration is set up, which may be heard in the test ear.

The presentation of a narrow-band masker to the non-test ear necessitates the placement of a transducer either over or in the canal of the non-test ear. This occlusion of the non-test ear results in an apparent improvement in the bone-conduction threshold in that ear. This occlusion effect is frequency dependent, and must be accounted for by the masking applied to the non-test ear.

Another factor affecting the measurement of bone-conduction is the placement of the vibrator on the head. Forehead placement stimulates both cochleae at approximately equal levels, but requires a higher vibration input than does mastoid placement to produce the same threshold sensation. This placement factor gives the appearance that forehead thresholds are approximately 10 dB less acute than mastoid thresholds.

The remaining three factors which the author reviews are all physical influences which may disturb the measurement process. The force of application of the bone vibrator to the head is known to affect the resulting thresholds. Low coupling force, in the range up to 3.5 newtons, leads to unacceptable variation in the measured thresholds; coupling forces greater than 7.5 N are considered to be painful to most subjects. The author suggests that 4.5 N, within narrow limits, would be a preferable standard coupling force.

The problem of sound radiation (by air) from the bone vibrator occurs mainly in the measurement of normal bone-conduction thresholds at frequencies greater than 1.5 kHz. The author describes a solution to this problem: over the ear is fitted a tube, lined with sound-absorbent material which does not cover or occlude the ear.

Lastly, ambient noise levels are discussed. Bone-conduction threshold measurements are performed with the test ear open, and thus vulnerable to ambient noise which might mask the audiometric signal. One-third octave band limits are listed; for such ambient noises within the test chamber, resultant errors in bone-conduction thresholds are negligible.

The author then describes a survey of bone-conduction thresholds employing 21 subjects with normal hearing. The survey, which incorporated all the points discussed above, used 6 different models of bone vibrator, all in use at the time of writing, with 3 different levels of coupling force. It was hoped that the data would assist the International Organization for Standardization in the formulation of appropriate standards.

STUDEBAKER (1967)

The author reports a study conducted to assist in the standardization of bone-conduction audiometry. One hundred and thirty-two young adults gave b-c thresholds by three vibrators (current at the time of writing), two vibrator locations (forehead and mastoid) and two methods of vibrator application (headband and a standard application force of 500 grams weight, g wt).

With the use of the headband, the three vibrators gave disparate threshold values across test frequency. For the standard application force, the differences between vibrators became insignificant, having only a systematic difference between forehead and mastoid site of application. For the standard application force, the threshold difference between sites (averaged over vibrator types) is given below; in all cases, the mastoid placement gave the better (more acute) threshold.

forehead threshold minus mastoid threshold, dB

frequency, kHz	0.25	0.5	1	2	4
difference, dB	13.9	13.7	12.6	9.9	6.2

The author notes that force of application should be made an integral part of any standard for the calibration of b-c vibrators, and procedures for b-c audiometry.

WESTON et al (1967)

Monaural bone-conduction thresholds were obtained for ten normally hearing subjects using mastoid and forehead placements for two different vibrators. Systematic and random differences between conditions were tested.

Ten normally hearing adults were tested, five males and five females within the age range 18 to 21 years. Bone-conduction thresholds were measured for the audiometric frequencies 0.25 to 6 kHz; in each case, the non-test ear was masked by a one-third octave band of noise centred at the tone frequency, and presented at 40 dB sensation level. The test signals were presented by one of two bone vibrators then in use; for simplicity, the two types will be designated US and FR here. Each vibrator was applied to either forehead or mastoid by headbands maintaining a force of 5.0 ± 1.0 newtons, regardless of application location. For either location, the test ear was shielded from air radiation of sound from the vibrator by a tube lined with sound-absorbent material, which would not occlude the test ear. In all, each subject gave four threshold determinations for each treatment formed by the 2 vibrators, 2 locations, 2 ears and 7 frequencies.

For measurement location, the two vibrators showed a frequency dependent difference, forehead mean threshold minus mastoid mean threshold as seen below.

	threshold difference, dB						
frequency, kHz	0.25	0.5	1	2	3	4	6
vibrator US	16.7	15.2	4.0	7.1	7.6	7.0	7.7
vibrator FR	17.0	15.3	7.8	7.0	7.1	6.0	5.0

For different bone vibrator types, this forehad minus mastoid quantity might assume different values.

Standard deviations are listed, showing the variability associated with subjects and ears:

frequency, kHz	0.25	0.5	1	2	3	4	6
mastoid							
US	5.1	6.0	7.4	6.8	7.2	5.7	6.8
FR	3.4	4.6	7.0	6.2	6.0	5.5	7.5
forehead							
US	2.8	6.9	6.6	6.9	6.6	6.1	7.2
FR	3.2	6.5	6.5	6.5	6.2	5.6	7.1

The authors interpret these results as indicating that at 1 kHz and above, variability does not depend upon vibrator or placement. For the lower frequencies, a placement-frequency interaction may be seen.

GUNDERSEN (1973)

Improvements in bone-conduction thresholds are reported for otosclerotic patients treated surgically with wire-and-fat prostheses. The patient sample comprised 314 males and 573 females, all between the ages of 30 and 79 years, and all with negative noise exposure histories. The surgery resulted in the b-c improvements listed below, which are averaged over all 887 subjects.

frequency, kHz	0.25	0.5	1	2	4
b-c improvement, dB	8.3	11.6	12.0	11.8	9.0

These differences between pre- and post-operative b-c thresholds indicate that the sensorineural hearing loss seen with otosclerosis is, in part, false or artefactual. In cases of stapes fixation in the oval window, bone-conduction thresholds are artificially elevated, as described by CARHART (1950), and do not indicate true cochlear function.

BAVOSI and RUPP (1973)

Fifteen normally-hearing subjects gave bone-conduction thresholds, with the vibrator positioned on the mastoid process by four different methods. The four placement methods under test were:

1. the vibrator was placed by the testing clinician, so as to avoid the vibrator touching the pinna, and without consulting the subject;
2. the subject adjusted the placement to give optimal loudness of a 1 kHz signal;
3. the pinna was taped down to intentionally contact the vibrator, a situation avoided in good clinical practice; and
4. the pinna was pulled forward by tape, to avoid contact with the vibrator.

For each placement, each subject gave b-c thresholds at the frequencies 0.25 to 4 kHz, by a manual, 5 dB step ascending method.

In comparison with the usual practice of clinician placement of the bone vibrator, no significant change of threshold was observed for the subject's placement or pinna taped forward conditions. With the pinna touching the vibrator, slightly improved (more acute) thresholds were observed; the authors attribute this to an air-conduction path resulting from this poor clinical practice.

RICHTER and BRINKMANN (1981)

As a contribution to international standardization, bone conduction thresholds were determined in units of force as the measure of vibratory input to otologically normal, young ears. Thresholds were determined for mastoid and forehead placement of the bone vibrator, with masking applied to the non-test ear. Each vibrator placement was tested using 25 young people (50 ears). As the subject groups were not identically the same individuals, it is not appropriate to compare mean threshold values between placement locations. It is safe to comment, however, that the mastoid placement required approximately 10 dB more vibratory input to elicit the sensation of hearing the test tone.

Comparison of threshold standard deviations is informative, if one keeps in mind the fact that the statistic contains variation between individuals as well as variation between placements.

	standard deviations of b-c thresholds, dB							
freq., kHz	0.25	0.5	1	2	3	4	6	8
mastoid	6.1	5.8	7.6	8.0	6.1	8.3	7.1	8.0
forehead	5.8	6.9	5.5	6.9	6.9	6.3	5.3	6.7

The general impression is that forehead determinations of b-c thresholds are less variable than mastoid thresholds. The magnitude of the forehead advantage is difficult to quantify, as the values listed are from slightly different subject groups.

GATEHOUSE and BROWNING (1982)

The bone-conduction thresholds observed in cases of conductive hearing loss are artificially elevated, and do not directly indicate the state of cochlear function. A lower bound on the magnitude of this artefact (the Carhart Effect) may be estimated from the difference between pre- and post-operative b-c thresholds in cases of conductive hearing loss. The authors feel that the effect has been underestimated in the past, and would be larger if appropriate selection criteria were applied to cases studied. Three conditions are suggested to select successful surgical cases.

Using their three criteria, the authors selected 103 stapedectomy patients from records available to them. Differences between pre- and post-operative b-c thresholds are given for these cases, as new estimates of the magnitude of the Carhart Effect. The criteria were also applied to data published by Ginsberg et al (1978); the re-analysis of these data resulted in new estimates of the Carhart Effect which are also given here.

frequency, kHz	0.25	0.5	1	2	4
authors' estimate	-	5.0	7.8	11.7	5.1
Ginsberg re-analysis	2.6	5.7	10.6	12.4	8.0

The authors are satisfied that these values are very similar to those originally reported by CARHART (1950).

It is argued that any restorative surgery, with the use of a middle ear prosthesis, is unlikely to result in normal transmission of sound energy through the middle ear. Thus, post-operative b-c thresholds could well still include an indeterminate residual artefact (apparent b-c loss). The implication is that, for any case of conductive hearing loss, b-c thresholds will give an inaccurate, artificially worsened, estimate of true cochlear function, even when corrected to account for the Carhart Effect.

BROWNING (1986)

In his discussions of conductive and mixed conductive-sensorineural hearing losses, the author emphasizes that bone-conduction thresholds are not a true measure of inner ear function. Whenever a conductive deficit is present, the b-c thresholds are artificially raised, and must be adjusted (toward audiometric zero) by subtracting the representative corrections given below.

frequency, kHz	0.25	0.5	1	2	4
correction, dB	6	10	15	16	11

LAU (1986)

A study was devoted to the variation of bone-conduction thresholds due to different forces coupling the bone vibrator to the head. British and International standards recommend a coupling force of 5.4 ± 0.5 N or 550 ± 49 g wt; this study systematically varied the force of application from 250 to 750 g wt, in intervals of 100 g wt.

Thirty-two subjects took part in the study, after normal hearing was verified by air-conduction audiometry. Bone-conduction thresholds were determined for these subjects at 0.25, 0.5, 1, 2 and 4 kHz, using a research vibrator from which acceleration and force levels could be measured during use on each subject's mastoid. As threshold excitation levels were determined directly for each subject, it was not necessary to measure equivalent threshold levels using an artificial mastoid.

The subjects were divided into groups of equal numbers. One group gave thresholds with vibrator coupling forces of 250, 450 and 650 g wt; for the other group, the forces were 350, 550 and 750 g wt. Considering acceleration levels measured at the head, coupling force had little or no effect upon the threshold levels for the frequencies 0.5 kHz and above. For 0.25 kHz, threshold acceleration levels were observed to become 3 to 4 dB more acute as the coupling force increased, 250 to 650 g wt for one group, 350 to 750 grams for the other. When threshold was quantified in terms of vibratory force applied to the head, the major effect was observed at 0.5 and 1 kHz. For these frequencies, increasing the coupling force by 400 g wt caused the thresholds to become <u>less</u> acute by 4 and 6 dB at 0.5 and 1 kHz, respectively.

Two points should be added to the author's report. The coupling force range employed in this study includes any which might be applied by bone-vibrator headbands used in clinical practice. The range of forces employed would give a sensation of 'light pressure' to 'definitely painful'. The change of coupling force produced changes of threshold for only one or two frequencies, and then only on the order of 5 dB. Such a small change of threshold value could well be overlooked as b-c measurement error, and certainly of no clinical or diagnostic importance.

Conclusions on Bone-conduction Threshold Variability

As seen by the reviews above, b-c threshold measurements suffer from a number of fundamental drawbacks, as summarized below.

1. As the test ear is uncovered, ambient noise levels are required to be very low, lower in fact than for earphone testing, if normal b-c thresholds are to be measured.

2. At present, bone vibrator technology influences unduly the measurement method for b-c thresholds. Forehead placement of the vibrator gives better repeatability of measurement, but the vibrators have insufficient sensitivity and dynamic range to excite the sensation of hearing in all cases where bone-conduction audiometry would provide useful diagnostic information. Mastoid placement renders the vibrators sufficiently sensitive, but location of the vibrator so close to the ear makes air-radiated sound a problem for higher frequency test stimuli.

3. No matter where the vibrator is placed, both cochleae receive the vibratory input. Masking, in some form, must be applied to the non-test ear, to ensure that the test signal is heard in the test ear. As seen previously in the Audiometric Method chapter, masking is a time-consuming process, requiring many intermediate thresholds for the determination of a single masked b-c threshold.

4. Although of no concern in the case of normal or near-normal hearing, the final condemnation of b-c audiometry comes in the form of the Carhart Effect. In cases where the gap between air- and bone-conduction thresholds would provide valuable diagnostic information, a systematic error is known to exist, which in individual cases cannot be exactly quantified. Where a conductive hearing deficit exists, b-c thresholds have been demonstrated to give an erroneously pessimistic estimate of the state of the cochlea behind the conductive blockage. If such a conductive loss were present with a cochlear loss being assessed for compensation purposes, b-c thresholds subject to a 10-15 dB Carhart Effect might well result in an inaccurate disability or handicap assessment.

AUDIOMETRIC ZERO AND OTOLOGICAL NORMALITY

For the measurement of hearing sensitivity, it has proved convenient to specify the acuity of any individual ear, for a particular frequency, in relation to an agreed audiometric zero, rather than in terms of sound pressure level. This has the effect of adopting a frequency-specific reference pressure, the normal hearing threshold, instead of using an arbitrary reference pressure common throughout acoustics. By this change of reference, the hearing acuity of any particular ear may be easily compared with an agreed 'normal' level.

For the purpose of defining the audiometric zero, the various standards bodies rely upon hearing threshold surveys employing otologically normal persons. Such a person is defined by the seemingly straightforward phrase, contained in ISO/R389-1964:

"... a person in a normal state of health who is free from all signs or symptoms of ear disease and from wax in the ear canal, and who has no history of undue exposure to noise."

Taking this definition at face value, a subset of all otologically normal persons, presumably of both sexes, is used to define young, normal hearing. Hearing thresholds are determined, under strictly controlled conditions, for "an adequately large number of ears of otologically normal subjects within the age limits of 18 and 30 years inclusive". The hearing threshold of each member of the subject group is 'captured' by measurement of the threshold signal in a closely-specified calibration device. Once individual thresholds are 'captured', a group threshold may be derived, for transfer to any other suitable transducer, be it earphone or bone vibrator, so that calibrated test signals may now be presented to new test ears.

This process of 'capturing' the audiometric zero deserves closer inspection, in order to appreciate the qualifications inherent in the standardization process, and how such qualifications bear upon practical hearing measurement. For the survey phase of the process involving an otologically normal ear (as defined above), a specified type and model of transducer (earphone or vibrator) is located correctly on the test ear or mastoid bone, with a specified force of application. Using signals of specified character and closely controllable magnitude, the transducer is energized for the determination of hearing threshold by any accepted technique of manual audiometry. Once a behavioural threshold is established for the survey ear, the transducer is removed from the ear and placed correctly, with a specified force of application, upon an electroacoustic or electromechanical calibration device, used for earphones and bone vibrators respectively. The audiometric transducer is then energized with the same signal which previously produced the behavioural threshold. In the case of an earphone, the sound pressure level developed in the electroacoustic device (there are two sorts in common use, the acoustic coupler and the artificial ear) is recorded as an Equivalent Threshold Sound Pressure Level (ETSPL). For a bone vibrator, the electromechanical device is called an artificial mastoid, and the datum is an Equivalent Threshold Force Level (ETFL). If this process is repeated for a sufficiently large number of otologically normal ears, the modal value of the data ensemble may be used to define the Reference Equivalent Threshold Sound Pressure Level (RETSPL) or Reference Equivalent Threshold Force Level (RETFL). If the process is performed over a number of test frequencies, the resulting collection of RETSPL's or RETFL's will define an audiometric zero for young, normal ears hearing by air or bone conduction as appropriate.

From the description above, it will be clear that the standardization process is based upon the fulfillment of both general and highly specific conditions. Otologically normal ears, especially within the required age range, may be found anywhere in the world if sufficient effort is devoted to the screening or selection process. This screening process will be discussed later. The audiometric zero determined for such young, normal ears is not, however, a unique set of sound pressure levels listed by frequency. Rather, audiometric zero is a concept realized using one of a set of specific air-conduction earphones working into the known volume (strictly a known acoustic load impedance) of a specified coupler or artificial ear; for bone conduction, a vibrator is applied to a specified artificial mastoid. As might be expected, national standards bodies began by separately developing standards of hearing thresholds involving a wide range of transducers and calibration devices. As an example, early British work, reported by Dadson and King (1952), determined the normal threshold of hearing for tones produced by earphone type 4026A, manufactured by Standard Telephones and Cables, Ltd. The RETSPL's for this type of earphone were specified as measured in an artificial ear as specified in British Standard 2042:1953.

For the development of International Standards, contributions were taken from participating nations in the form of RETSPL's for preferred national patterns of earphone and artificial ear or acoustic coupler. As each national contribution purported to specify the hearing of young, otologically normal ears, all national contributions were deemed to be equivalent, but different, realizations of the threshold of hearing. Such a parallel listing may be found in ISO Recommendation 389 (1964). With developing technology, however, certain of the preferred national patterns listed in the ISO Recommendation are no longer available; some earphones are no longer produced commercially, and various patterns of acoustic couplers or artificial ears have been recognized as unreliable or difficult to manufacture. The audiometric zeroes embodied in such obsolete equipment, dropped from subsequent standards, have not been lost, however. An obsolete threshold zero may be transferred to more widely available transducers by a threshold balance technique, as suggested in British Standard 2497:1954. Such transference of audiometric zero from one pattern to another will have introduced an unknown degree of subjective variation, with the interposition of a second panel of listeners between the first set of otologically normal listeners and the revised threshold values. In addition, as the various national standards bodies have agreed on common patterns of earphones and calibration devices, slightly discrepant values of audiometric zero have evolved from national contributions to the original document. These discrepancies had to be reconciled by compromise between the contributing nations, in keeping with the aim of International Standards as statements of voluntary consensus between national standards bodies.

At present, the earphones in most widespread use throughout British audiometry are the TDH-39 and TDH-49. The RETSPL values for these two patterns of earphone are given in British Standard 2497:Parts 5 and 6:1988. For bone conduction audiometry, vibrators B-71 and B-72 are widely used, with RETFL values given in BS 6950:1988. For each of the British Standards listed, there exists an International Standard identical to its British counterpart.

Otological Normality

From the discussion above, it will be clear that the definition and realization of audiometric zero depends crucially upon the concept of otological normality. Having seen the ISO (and British Standard) definition above, it will prove useful to see examples of the interpretation and application of that definition to standardization matters. The International Standard ISO 7029-1984, which gives the relation between age and hearing threshold level for otologically normal persons, provides the most recent re-affirmation (by example) of the concept of otological normality. Listed in the references of the Standard are a number of research studies which were directly utilized in setting the Standard. Each of these individual sources provides an example of the selection process employed to obtain a more-or-less highly screened subject sample; each such sample, by its use in setting the International Standard, is confirmed as an authentic example of normality. It will be instructive to review the sources (at least those in English) of ISO 7029-1984, to assess the underlying strength of the ISO definition and the necessary rigour of its application.

The Reviews

HINCHCLIFFE (1959a)

A survey was undertaken to measure the threshold of hearing in a random sample of the rural U.K. population. The subjects were chosen from the age range 18 to 24 years in two rural districts, one in Wales, the other in Scotland. The selection process is of interest here.

Of all the threshold data collected from those attending for audiometry, certain exclusions were made to establish an otologically normal sub-sample. An individual ear would be excluded if there was a history of ear surgery (myringotomy or surgery on the pinna were not considered sufficient grounds for exclusion). An ear would be excluded if otitis externa was present, if the drum was scarred or perforated, if there was evidence of fluid in the middle ear, or if the Rinne tuning fork test gave a negative (abnormal) result; all these exclusion criteria indicate ear disease. An ear would also be excluded if the canal was occluded by impacted wax which could not be conveniently removed.

Two more exclusions were made on the basis of questionnaire responses. A person would not be considered otologically normal if he or she answered affirmatively to the question "Is there a particular incident of any sort that you think might have affected your hearing (for example, an explosion, a blow on the ear, or such like)?". Individuals were also excluded if a report was given of recurrent attacks of vertigo associated with nausea and vomiting, together with tinnitus in either ear.

The hearing of males at the frequencies 3, 4 and 6 kHz was less acute than that for females. This gender difference was attributed to cochlear damage in the males, due to exposure to the noise of firearms. At the frequencies mentioned, only the female data were used as a check of the British audiometric zero; for all other frequencies, both male and female data were analysed. The exclusion of male data for the frequencies 3, 4 and 6 kHz was the result of questioning regarding noise exposure at work. Over half of the clinically normal males answered affirmatively to the question "At any time, is your job so noisy that you have a raise your voice to be heard?". The subjects were also questioned about their use of rifles in military service; sporting guns were not considered. The effect of acoustic hazards is seen in the median thresholds for 4 kHz, given below.

Sample	median threshold at 4 kHz, dB
clinically normal female ears	0.0
clinically normal male ears with:	
i) no history of occupational noise or military riflefire	1.8
ii) history of occupational noise, but no military riflefire	3.6
iii) military riflefire, but no occupational noise	11.5

These hearing losses in males, relative to the normal hearing of females, were found in these young people 18 to 24 years old. Even a relatively short duration exposure to occupational noise is seen to affect the hearing threshold. Use of firearms seems to be especially hazardous to the hearing.

GLORIG and NIXON (1962)

A survey of hearing threshold levels was conducted among 2518 American men, ranging in age from over 20 years to under 80 years. From these men, a subgroup gave thresholds which were used in the preparation of ISO 7029, giving the threshold of hearing as a function of age and sex for otologically normal people. The selection process used for this study bears upon the definition of audiometric zero, and of presbyacusis for the otologically normal population.

The survey was conducted among men, all professionals or office workers, drawn from three sources. One group comprised 1391 members of staff at two large research organizations. The second and third groups consisted of 502 otolaryngologists and 625 other doctors in attendance at two separate meetings of their respective professional societies. Each man was carefully questioned regarding ear disease, blows to the head resulting in unconsciousness, and any episode thought to have produced a hearing loss. Each man was also questioned about exposure to gunfire, either military or civilian, or to explosions of any kind. Detailed histories were made of the durations of any noise intense enough to make conversation difficult at close range. Otoscopic examination or tuning fork tests are not reported.

Of the 2518 men surveyed, 473 had no history of ear disease and no history of noise exposure of any kind. From this screened sample, median thresholds of right ears are given for the frequencies 1, 2, 3, 4 and 6 kHz, separated by decade of age. For the median hearing levels for each frequency, the authors present regression coefficients from a least-squares curve-fitting procedure, allowing the prediction of hearing loss at any of the specified frequencies at any age between 20 and 80 years. The resulting values represent only males questioned to exclude ear disease and noise exposure.

CORSO (1963)

This study was conducted to obtain data on the hearing threshold levels of male and female Americans, over the age range 18 to 65 years, who had not suffered exposure to high level noise. The results of this study were used in the preparation of ISO 7029 which defines the threshold of hearing as a function of age and sex for otologically normal persons. The processes used to select otologically normal subjects bears upon the concepts of presbyacusis and audiometric zero.

The 918 subjects tested in the hearing survey were selected from six age ranges : 18 to 24 years; 26 to 32; 34 to 40; 43 to 49; 51 to 57; and 59 to 65 years. The youngest group were drawn from a university undergraduate student population. The remaining five age bands were filled from the electoral register. In order to participate in the survey, each subject had to complete a three-stage process: 1) a hearing questionnaire was administered by an interviewer, followed by; 2) a detailed otological examination, which itself was followed by; 3) the audiometric test within 48 hours.

The questionnaire had three parts. The noise history portion sought information on periods of noise exposure resulting from occupation, trade education, residence near an airport or in an industrial district, noisy leisure activities, and modes of customary transport. Information on periods of military service was also sought, particularly if weapons were used or a set minimum flying time was exceeded. Strict rejection criteria were applied.

All subjects were given an otological examination covering the pinna and ear canal, the mastoid bone, the eardrum and ossicles, and the eustachian tube, nose and throat. Within each anatomical zone, evidence of certain disorders was sought. For example, the tympanic membrane was examined for signs of current inflammation, atrophic scars, non-transparency, retraction, thickening and immobility of the drum. The findings of the otological examination were critically reviewed and evaluated by a consultant in otology. Each subject was rated as a "pass" or "fail" on the basis of negative or unfavourable findings.

On the bases of the questionnaire and otological examination, as reported, the selection of subjects for audiometry was quite stringent. The thresholds from this highly selected sample are reported as means and standard deviations for each sex and age range, for each audiometric frequency from 0.25 to 8 kHz.

TAYLOR et al (1967)

Hearing threshold levels were surveyed by manual audiometry among 171 female school teachers in Dundee. The results from this survey were used in the preparation of ISO 7029, giving hearing thresholds as a function of age and sex for otologically normal persons. The selection process applied to the Dundee teachers bears upon the definition of audiometric zero and the specification of presbyacusis.

Two hundred and nine female schoolteachers, over the age range 18-64, agreed to participate in the hearing survey. Before performing the audiometry, all subjects were interviewed to elicit a complete history relevant to hearing. A few music teachers were eliminated due to possibly damaging noise exposure associated with teaching. In the medical history, particular attention was paid to concussive head injuries and administration of ototoxic drugs. There followed an otological examination of the ears and pharynx. A subject was considered to be normal if:

1. both ear drums appeared normal;
2. no history of ear disease, past or present, was given;
3. neither drum was obscured by wax;
4. no upper respiratory tract infection was present at the time of test; and
5. no history of excessive noise exposure was given (industrial noise, shooting, or explosions).

Two hundred and three of the teachers fulfilled the criteria of otological normality and performed manual audiometry at the frequencies 125 Hz to 8 kHz, using an attenuator step of 2.5 dB. The survey results are reported as mean HTL's relative to the British Standard current at the time of writing. Mean values are reported for each frequency, for subjects within the age ranges 18-24, 25-34, 35-44, 45-54 and 55 - 64 years.

HINCHCLIFFE and JONES (1968)

A survey of hearing was conducted among the residents of a small town in Jamaica. The population in the target age group, 35-74 years inclusive, numbered 676, of whom 81.5% were tested. The data from these men and women were used in the preparation of ISO 7029, giving the threshold of hearing as a function of age and sex for otologically normal people. The selection process used for this study bears upon presbyacusis in an otologically normal population.

In the area of the hearing survey, there was only one factory; noise in this factory was judged to constitute no hazard to hearing. It would seem that this decision was considered sufficient to eliminate any possibility of undue exposure to excessive noise. However, it is suggested by the authors that the male subjects may have been exposed to some noise from rifles and sporting guns. The only other screening mentioned by the authors is the exclusion of ears with a conductive hearing loss, as determined by the Rinne tuning fork test.

The selection of subjects for inclusion in this study does not seem to be stringent enough for the inclusion of the audiometric results in an International Standard. In spite of the low level of subject screening, this Jamaican sample shows better hearing for age than do British samples subjected to more stringent screening. The better hearing appears to justify inclusion in the data sample for ISO 7029.

KELL et al (1970)

A survey of hearing was conducted on the island of Westray in Orkney, off the northern coast of Scotland. Of a total population of 602 persons over the age of 15 years, 580 took part in the study. A subset of the population were determined to be otologically normal; the data from these individuals, both male and female, were used in preparation of ISO 7029. The selection process for otological normality will be reviewed, as it bears upon both audiometric zero and presbyacusis.

All adults (age greater than 15 years), who were willing and capable of participating, completed a questionnaire before otological examination and audiometric testing. The questionnaire sought details of past or present noise exposure, including service in the armed forces, and a medical history with episodes likely to affect the hearing: head injuries; past or present ear pathology; or exposure to drugs (presumably ototoxic). A clinical otological examination was made, including examination of the eardrum and pharynx, and a Rinne tuning fork test (seeking a large conductive hearing loss). If cerumen was found in the ear canal, it was removed by syringing.

To obtain a suitable otologically normal population for the study of hearing threshold with age, it was necessary to reject a number of subjects failing to meet the following criteria:

1. normal eardrums observed otoscopically;
2. no history of ear disease, past or present;
3. no upper respiratory tract infection at time of test;
4. no history of exposure to excessive noise (occupational, shooting, war service, or explosions).

Any subject with an observed abnormality in one ear (with reference to items 1 and 2 above, presumably) was rejected, even if the other ear appeared normal. On these criteria, 103 persons were rejected on medical or noise-exposure grounds. Of the remaining 477 adults participating, 463 were able to give complete audiograms by a manual method performed at the frequencies 125 Hz to 8 kHz, using a 2.5 dB step attenuator.

The survey results are reported as mean HTL's relative to the British Standard audiometric zero current at the time of the research. Mean values are given for each frequency, for subjects in the age ranges 15-24, 25-34, 35-44, 45-54, 55-64, 65-74 and 75+ years. The authors' results have been corrected to the current audiometric zero specified in BS 2497:Part 5:1988, and are listed below as mean HTL's for the youngest age group. These listed values should closely approximate true audiometric zero, but certain discrepancies may be observed.

frequency, kHz	0.25	0.5	1	2	3	4	6	8
corrected mean, dB	7.6	3.1	0.9	1.3	1.1	1.4	9.7	2.1

For most frequencies, the mean HTL is close to the standard zero. For two frequencies, 0.25 and 6 kHz, the mean otologically normal threshold deviates by considerably more than 5 dB from the standard zero giving the young subjects an apparent hearing loss.

Application of Otological Normality to the Standards-making Process

From the reviews above, it may be seen that the definition of otological normality has been applied with flexibility, certain relaxations of the definition being condoned. In some cases, threshold data are accepted for application to the Standard from subjects of uncertain, even unknown, noise exposure. Certain other sources contain data from subjects outside the stated age limits. Such latitudes are understandable in the standard-making process, however; certain compromises must be allowed in order to gather sufficient data from which to draw conclusions. Compromise may be thought of as a catalyst, rather than a poison, for the standardization process.

Audiometric Zero

In the preceding sections, the selection of otologically normal subjects has been reviewed, and reference made to the use of such subjects in the determination of an audiometric zero. Once the zero is published as a British or International Standard, it is 'installed' in audiometers for widespread use. Once the zero becomes available, it may then undergo further validation testing, away from the national standard laboratories, on further samples of otologically normal listeners.

What follows is a sampling of research reporting the hearing thresholds of young otologically normal ears, referenced to the current British (or equivalent International) audiometric zero, for both air and bone conduction. By keeping a watch on the ever-growing sample of normal thresholds, it is possible to assess the accuracy of the standardized (compromise) values of audiometric zero.

The Reviews

DELANY et al (1966)

The authors describe a preliminary study of the feasibility of using the self-recording audiometric technique with children. A number of children, age 6.5 to 17 years, were examined otoscopically and had medical histories recorded, in order to select an otologically normal sample. Those found suitable were given instructions in the technique, and then tested at the frequencies 0.5 to 6 kHz. The left ear was tested first, followed by the right ear, concluding with a partial repeat of the lower frequencies in the left ear.

The results were reported as mean hearing thresholds at each frequency, listed for various age groups, in dB relative to the audiometric zero specified in BS 2497:1954 which does not differ greatly from current standards ISO 389-1985 and BS 2497:Part 5:1988. For several frequencies, the mean thresholds show improving values with increasing age. Listed below are the results for the oldest group, mean 15.5 years, of 58 ears. Also listed are the independent otologically normal control groups, one of 60 ears, mean age 16 years, and another of 66 ears, mean age 22 years. The values for each group have been adjusted using a correction factor determined by the authors, with the intention of relating self-recorded thresholds to those determined by a manual method using 1 dB attenuator steps. By this device, the HTL's listed for the children and controls have been made directly comparable to the ISO audiometric zero.

These subject groups were screened for otological normality, and might be used to define audiometric zero. Only the older controls fall into the 18-30 age range currently used to define audiometric zero.

	mean threshold, dB HL					
frequency, kHz	0.5	1	2	3	4	6
children						
(15.5y)	2.5	0.5	1.2	2.9	1.2	8.3
controls						
(17y)	1.7	-0.8	0.7	3.2	1.9	8.5
(22y)	-1.3	-1.6	-0.2	-0.2	-0.7	5.3

From these values, derived for the present work, it is clear that the Reference Equivalent Threshold Sound Pressure Level for 6 kHz is set at too low a value by approximately 5 dB. Using the ISO audiometric zero, even otologically normal young people show a hearing loss of 5 dB at 6 kHz.

RICE and COLES (1966)

Thresholds of hearing were determined for two samples of otologically normal, young people, aged 16 to 25 years. One sample comprised both male and female subjects drawn from a university student population; the other sample comprised Royal Marine recruits, all male.

The two samples were screened to eliminate any abnormality observable by otoscopy, and past history of exposure to intense noise. After self-recording audiometry, subjects who gave "poor tracings" were eliminated (criteria for such tracings are not given); also eliminated were those young people found to have "gross hearing loss". The final samples were 168 ears from the mixed-sex university group, and 202 ears from the Royal Marine recruits.

The results of the self-recording audiometry are reported in the form of median Equivalent Threshold Sound Pressure Levels for the type of earphone used, as measured on a standard acoustic coupler. For present purposes, the results are listed as median hearing levels with reference to the audiometric zero specified in BS 2497:Part 5:1988. A correction of 3 dB has been made to the reported results, in order to account for the more acute thresholds known to result from self-recording audiometry; by this means, the values listed below are those which would have been determined by a manual technique.

median thresholds, dB HL

frequency, kHz	0.25	0.5	1	2	3	4	6	8
university	-	1.3	-0.5	-1.6	0.1	-0.8	5.4	-
Royal Marines	3.8	1.5	-0.7	-2.5	-0.6	0.8	2.8	-3.4

The majority of the survey results are close to zero. The 6 kHz results show the largest deviations from zero, by +5.4 and +2.8 dB for the university and Royal Marine samples, respectively. It would appear that the International and British Standards set too stringent a value for audiometric zero at this frequency, with the result that young, normal ears show a small but systematic hearing loss where none exists.

TAYLOR et al (1967)

Hearing thresholds were surveyed among female school teachers in Dundee, to determine the relation between age and hearing levels for highly screened, otologically normal persons. The screening process has been reviewed here, in a previous section.

Mean threshold values were reported for a number of age groups; the data for the 18-24 year group of 46 teachers is of interest here. The authors' results have been corrected to the current audiometric zero, as specified in BS 2497:Part 5:1988, and are listed below as mean HTL's for the youngest age group. Medians have been derived and corrected for this group; these values should define true audiometric zero, but certain discrepancies may be observed.

frequency, kHz	0.25	0.5	1	2	3	4	6	8
corrected mean, dB	4.5	1.5	-0.7	-2.0	-2.2	-2.2	7.0	2.5
corrected median, dB	5.2	1.5	-0.4	-2.1	-2.2	-2.1	7.6	2.3

For most frequencies, the median HTL is close to the standard zero. For two frequencies, 0.25 Hz and 6 kHz, the standard zero deviates by more than five dB from the median, giving the normal subjects an apparent hearing loss.

AIELLO and COPELAND (1973)

A study was conducted to determine systematic differences between thresholds determined using three different models of noise-excluding headset. A standard earphone was used to determine a baseline threshold. Twelve subjects, with mean age 22 years, were selected for otoscopic normality and negative history of ear pathology and tinnitus. These subjects gave right ear, self-recording thresholds for the frequencies 0.25 to 8 kHz.

The mean HTL's achieved using the standard earphone are presented here in relation to the audiometric zero of ANSI (1969), which is equivalent to BS 2497:Part 5:1988. The values here have been corrected to account for known differences between self-recorded and manual thresholds.

frequency, kHz	0.25	0.5	1	2	3	4	6	8
threshold, dB HL	0.8	2.6	0.6	-1.7	1.9	3.1	3.8	4.6

These HTL's for normally-hearing young people suggest that audiometric zero for the higher frequencies, 4, 6 and 8 kHz, is set at too stringent a level.

HANSON and FEARN (1975)

Five hundred and five young people, aged 18-25 years, performed audiometric tests, to determine the effect of amplified popular music upon hearing. This sample of young people was separated into those who regularly attended popular music events, and those who attended such events three or fewer times per year. A rigorous selection process was applied, in order to achieve otological normality within both the regular- and seldom-attender groups.

Otological examination selected those subjects with a healthy eardrum, that is, intact, unscarred and with no retraction or tympanosclerosis, and with no evidence of otitis media. Tuning fork tests were performed; a central Weber result was required, as was a favourable Rinne result. Subjects were rejected from the original large sample if there was history of ear disease, exposure to gunfire or industrial noise, recent infection of the upper respiratory tract, removal of the tonsils or adenoids, or a family history of deafness.

If an accumulation of wax prevented viewing of the drum, the audiometric results were retained in the sample if those results were better than the mean. A similar relaxation was applied for those subjects with history of tonsil or adenoid removal, or family history of deafness.

The final sample comprised 50 regular-attenders and 29 seldom-attenders, all highly screened for otological normality, and who had been tested several times by manual audiometry. The mean HTL's are listed below for each group:

mean threshold, dB HL							
frequency, kHz	0.5	1	2	3	4	6	8
seldom-att.	0.6	-0.2	-0.1	-0.9	-2.1	3.2	3.9
regular-att.	3.1	1.7	1.1	3.4	1.2	4.9	5.1

The authors attributed the less acute thresholds of the regular-attenders to their exposure to loud music. No explanation was offered for the approximate uniformity of "hearing loss" across frequency. However, the authors were able to discern an embryonic "noise notch" at 3 kHz, and offered the unhelpful comment that the frequency distribution of amplified music may have a damage potential different from that of typical industrial noise.

Turning to an aspect of this work not addressed by the authors, the seldom-attenders may be considered to be an otologically normal sample consistent with the BSI definition. Thus, HTL's from these young people should define audiometric zero. There are differences from zero, however; those at 6 and 8 kHz are largest, indicating that the RETSPL's for these frequencies are standardized at too low a level. This seeming systematic error in the audiometric zero, specified in British Standards, results in all people showing artificially inflated high frequency hearing levels.

VOGEN and COPELAND (1976)

A study was conducted to establish the reliability of thresholds determined using a TDH-39 audiometric earphone, and using the same earphone within a noise-excluding headset. Thirty subjects, of mean age 21 years, were chosen for otoscopic normality and negative history of ear pathology or tinnitus. These normal-hearing subjects gave right ear manual thresholds for the frequencies 0.25 to 8 kHz.

The mean HTL's achieved using the TDH-39 earphone are given here. The values are expressed relative to the audiometric zero specified in ANSI (1969). This standard is technically equivalent to BS 2497:Part 5:1988.

frequency, kHz	0.25	0.5	1	2	3	4	6	8
threshold, dB HL	4.1	1.9	2.2	0.4	0.9	4.5	4.7	2.7

These threshold values for otologically normal young people suggest that audiometric zero is set at too stringent a value for extreme frequencies, 0.25, 4 and 6 kHz.

ROCHE et al (1977)

Hearing threshold levels were determined in children 6 to 17 years of age. The thresholds were related to medical history, noise exposure, otological examination results, and physical size and maturity. Two hundred and twenty-four American children participated in the study, without any selection to enter the sample. Before audiometric testing, data was obtained on each child by means of a questionnaire. Noise exposure details were sought for recreational activities and part-time work, and for family and residential situation. An otological history was also obtained, with details of family deafness and medical history. An otological examination was also performed before audiometric testing. Both meati were inspected for accumulations of wax or signs of current inflammation. The drum was inspected; perforations, scars and the cone-of-light were noted as present or absent. The colour of the drum was also assessed for signs of previous or present middle ear infection. Upper respiratory tract infections or allergic reactions were noted. Following the preliminaries, all children went on to the audiometric testing; no subject was excluded on the basis of noise history or otological findings.

Hearing threshold levels were obtained at 0.5, 1, 2, 4 and 6 kHz, relative to the audiometric zero defined in ANSI (1969). In each case, the right ear was tested first. A manual technique was used, based upon a step size of 2 dB, to bracket the threshold by ascending and descending trials.

The hearing threshold results are reported for boys and girls, in the age groups 6-11 years and 12-17 years. For right, left and better ears, mean thresholds are given; minimum and maximum HTL's are given along with HTL's for 10%, 25%, 50%, 75% and 90% of each sample. Median thresholds were more acute than means, indicating some degree of skewness in the distribution of Hearing Threshold Levels. Such skewness could be taken to suggest that some (unknown) proportion of the sample showed threshold elevation associated with unfavourable noise history or ear disease.

Of the two age groups, the older gave the more acute thresholds; it was suggested that the younger children were not able to perform the audiometric task to the same standard of concentration as the older subjects. Girls gave more acute thresholds than did the boys; the girls' lead in physical and mental maturity is offered to explain the sex difference. Median HTL's are given below for boys and girls, aged 12-17 years. The right ear was always tested first, with the possibility of a learning effect; left ear HTL's are listed below by frequency.

	median threshold, dB HL				
frequency, kHz	0.5	1	2	4	6
boys (80 ears)	-2	-4	-4	0	2
girls (95 ears)	-4	-4	-6	0	0

These HTL values, although not from a sample strictly selected for otological normality, show trends seen before, suggesting that there is a frequency-dependent error in audiometric zero. The audiometer calibration values of ANSI (1969), which are identical to the comparable ISO and BS documents, result in slightly negative HTL's for the mid-frequencies, and a positive HTL for 6 kHz.

This report is included in the bibliography of ISO 7029, and has been indicated as influencing the listed values of hearing level by age and sex, probably as a check on the baseline age of the standard, that is 18 years. However, as no exclusions were made from the subject sample on the basis of otological findings or noise history, the sample of children must be regarded, in the strictest sense, as typical rather than otologically normal.

DIRKS et al (1979)

In an effort to assist in standardizing an audiometric zero for bone conduction, b-c thresholds were determined for 60 young otologically normal persons at three American laboratories. Monaural self-recorded thresholds were obtained using a B-71 bone vibrator, which complies with International Standards (and is widely used in British audiometry); the vibrator was applied to the test ear mastoid, in each case, with a static coupling force close to 5.4 newtons. The non-test ear was masked by a narrow band of noise, centred as appropriate at the frequency of each test tone, 0.25, 0.5, 1, 2, 3 and 4 kHz.

The mean thresholds from this sample of 60 otologically normal ears were reported in terms of force levels developed in an electromechanical coupler intended to mimic the properties of the human mastoid. For presentation here, the mean thresholds are given in dB relative to the British Standard b-c audiometric zero.

	mean b-c threshold, dB HL					
frequency, kHz	0.25	0.5	1	2	3	4
threshold, dB HL	-3.8	2.3	-2.4	2.3	-0.5	-2.7

The authors' values were not adjusted to account for subject group deviations from the air-conduction audiometric zero; such an adjustment would have transferred known a-c inaccuracies to the proposed b-c zero. The results of these researchers, reported as Equivalent Threshold Force Levels, were taken account of in the derivation of the Reference Equivalent Threshold Force Levels later specified in BS 6950:1988.

ROBINSON et al (1979)

A determination of the normal threshold of hearing by air conduction was made by self-recording audiometry for the frequencies 0.5 to 6 kHz. Special attention was given to the selection of otologically normal subjects from 108 individuals in the age range 18 to 30 years. Before audiometry, each subject completed a questionnaire to define his or her noise exposure history and to uncover episodes or conditions affecting otological health. Each subject also had both ears examined otoscopically and by the use of tuning fork tests.

Self-recording audiometry was performed by the method set out by the HEALTH AND SAFETY EXECUTIVE WORKING GROUP ON AUDIOMETRY (1978). Each subject gave threshold tracings for 0.5, 1, 2, 3, 4 and 6 kHz, first in the left ear, then the right and then again in the left. Thresholds were read from the right and left-repeat audiograms.

Results of the audiometry were given as mean HTL's for various subsets of the subject pool. Given below are mean HTL's against frequency for those subjects fulfilling the most rigorous interpretation of otological normality, that is, no unfavourable history or clinical findings whatever. The values listed here are referenced to the ISO 389 audiometric zero, and have been adjusted to account for known differences between thresholds determined by self-recording and manual audiometric methods.

frequency, kHz	0.5	1	2	3	4	6
threshold, dB HL	1.7	-1.3	-0.8	-1.1	2.0	3.4

The HTL's for the 11 otologically normal subjects should be identically zero; some fluctuation about zero is seen for these subjects, particularly at 6 kHz. The authors suggest that the calibration value for audiometric zero at this frequency is specified at too low a value, by 3 or 4 dB. This systematic error in audiometric zero was evident throughout the subject sample, not only the 11 otologically normal (not to say perfect) subjects for whom thresholds are listed.

HAUGHTON and PARDOE (1981)

A normative study was undertaken as a contribution to the process of standardization of Reference Equivalent Threshold Force Levels for bone-conduction audiometry. A number of otologically normal listeners gave b-c thresholds across the frequency range. Potential subjects were examined to exclude any with middle ear abnormalities. Each person completed a questionnaire concerning his or her otological history and any medical conditions relevant to hearing. The questionnaire was followed by otoscopy, tympanometry and acoustic reflex measurements, all to ensure normal conductive function. If necessary, excessive earwax was removed by syringing. Thirty subjects, comprising 14 men and 16 women, with age range 17 to 39 years, were found to be otologically normal and thus suitable for audiometry.

As a final verification of suitability for inclusion in a bone-conduction normal' sample, each subject gave self-recorded air-conduction thresholds for the frequencies 0.25 to 8 kHz. The first audiogram was given for the non-test ear, that is, the ear contralateral to the one chosen for the monaural b-c threshold series. This first a-c audiogram absorbed the expected learning effects. Two a-c audiograms for the test ear were performed over different sessions. The authors adjusted the mean threshold at each frequency by a small age correction, ranging from 0.2 dB at 0.25 kHz to 0.9 dB at 8 kHz. This was done to align the mean thresholds of their sample to the audiometric zero specified by British Standard for subjects of age range 18 to 30 years. The values have also been adjusted for presentation below, by adding 3 dB from the authors' values to account for known differences between thresholds determined by the self-recording and manual methods of audiometry.

mean a-c thresholds, dB HL

frequency, kHz	0.25	0.5	1	2	3	4	6	8
threshold, dB HL	2.0	-0.2	-1.5	-1.1	1.8	4.5	7.0	4.4

These values duplicate trends seen in the results of other researchers, suggesting that the audiometric zero for the higher frequencies, in this case 4, 6 and 8 kHz, are set at values too low to represent normal hearing. The authors accepted these mean air-conduction thresholds as final verification of otological normality for the 30 ears to be used for the bone-conduction normative study.

Following the a-c threshold measurements, b-c thresholds were determined by the self-recording method. The bone vibrator, meeting current International and British Standard specifications, was applied to the mastoid of the test ear with a static force of 5.4 newtons; no attempt was made to find a particularly sensitive region of the mastoid. The non-test ear was covered by an audiometric earphone. While the pulsed test tone was presented through the bone vibrator, the non-test ear was presented with a band of noise centred at the test frequency, and presented at a level verified sufficient to prevent detection of the test tone in the non-test ear. The level of the masker rose and fell in synchrony with that of the test tone. The threshold of each of the 30 test ears was determined in this manner for the frequencies 0.25 to 4 kHz. The mean thresholds are listed below, referenced to audiometric zero specified in terms of acceleration level by the then-current British Standard (BS 2497:Part 4:1972), and also in terms of force level which has since been adopted as the vibration measure (BS 6950:1988).

	mean b-c thresholds, dB HL					
frequency, kHz	0.25	0.5	1	2	3	4
accel.ref.	-2.2	-4.8	-7.3	-8.4	-1.2	-1.6
force ref.	0.9	-3.1	-0.7	-2.3	-0.3	-2.2

These values of normal b-c thresholds, expressed as dB relative to audiometric zeroes in terms of accelation and force, indicate that the subsequently adopted force standard is the more accurate, considering that no adjustment has been made for the self-recording method.

The authors note that b-c thresholds are seldom required on their own; b-c measurements usually accompany a-c thresholds. It would seem logical to link the air and bone standards so that a mean air-bone threshold difference would be observed for subjects without conductive pathology. The linking of standards would also make the air-bone threshold difference independent of audiometric method. However, such a linking would cause known inaccuracies of the a-c audiometric zero to be replicated in the b-c zero. The authors favour independent determinations of the b-c threshold of hearing for otologically normal subjects.

ARLINGER (1982)

A small study was performed to assist in the standardization of normal threshold of hearing at one-third octave preferred frequencies. Ten otologically normal subjects, four men and six women, all without undue noise exposure, participated in the study. The subjects, aged between 23 and 30 years, gave hearing thresholds at a number of standard and intermediate audiometric frequencies, using a manual, ascending 5 dB step technique.

The mean HTL's of the 20 ears are listed below for the standard frequencies. The listed values are relative to the ISO 389 audiometric zero (equivalent to BS 2497:Part 5:1988).

frequency, kHz	0.5	1	2	3	4	6	8
threshold, dB HL	2.8	2.0	0.8	-0.4	1.5	2.5	-0.3

These threshold values for normal-hearing ears shows a familiar pattern of a small apparent hearing loss at 0.5 and 6 kHz.

CARTER et al (1982)

A study was conducted to investigate the popular notion that amplified popular music causes hearing loss in young people. To investigate this question, a large group of subjects was sought among Australian young people : university students; office workers; and trade apprentices. In all, 944 young people, aged 16 to 20 years, took part in the study.

Each subject was interviewed to determine medical history, recreational pursuits, attendance at popular music events, and employment history. Each subject was also given a comprehensive ear, nose and throat examination, including removal of occluding wax, if present. A proportion of the subjects were found to be otologically normal, as set out in the ISO definition (also found in British Standards). This subset of the subjects was judged to be suitable for use in deriving standards of normal hearing.

The otologically normal subjects gave mean HTL's by frequency as listed below, in relation to the ISO audiometric zero current at the time of test.

frequency, kHz	0.5	1	2	3	4	6	8
threshold, dB HL	1.9	-0.5	-1.6	0.5	1.1	5.6	3.9

For the frequencies 0.5 to 6 kHz, the means are derived from HTL's for both ears of 656 young people of both sexes; for 8 kHz, the mean involves 490 subjects. From the values listed, it may be seen that the mean HTL's are quite close to zero, save for one frequency. At 6 kHz, the mean HTL for the otologically normal young people is more than 5 dB from audiometric zero. This trend has been seen many times in the reviews of this section.

(Returning to the question of amplified music causing hearing loss among Australian young people, the data revealed no trend between high frequency hearing threshold and reported number of attendances at music events.)

ROBINSON and SHIPTON (1982)

In an effort to assist in the international standardization of an audiometric zero for bone conduction, a-c and b-c thresholds were determined for a relatively large number of otologically normal young persons, aged 16 to 30 years. Air-conduction hearing threshold tests were performed on the basis of the ISO definition of otological normality, with strict and practical interpretations. Self-recording audiometry was performed at the frequencies 0.25, 0.5, 1, 2, 3 and 4 kHz. For the b-c tests, the definition of otological normality also included normal middle ear function verified by a normal tympanogram with the presence of acoustic reflexes. Bone-conduction thresholds were determined by the self-recording method at the frequencies listed above; the bone vibrator employed was one meeting International Standards and commonly used in British practice. Bone thresholds for each test ear were determined for three conditions applied to the non-test ear: not masked; and two levels of narrow-band noise masking.

The air-conduction thresholds are given below for those 37 subjects (74 ears) fulfilling the most stringent interpretation of the ISO otological normality definition. These mean values, relative to the ISO 389 audiometric zero (equivalent to BS 2497:Part 5:1988), have been adjusted to account for known differences in thresholds determined by the manual and self-recording methods.

air-conduction thresholds

frequency, kHz	0.25	0.5	1	2	3	4
threshold, dB HL	4.8	2.7	0.0	-0.2	0.1	0.4

Bone-conduction thresholds were reported as force levels measured using a standard electromechanical coupler. The mean values below, listed in dB relative to the b-c audiometric zero given in BS 6950:1988, represent the thresholds for 68 otologically normal subjects (136 ears), considering all three masking conditions.

bone-conduction thresholds

frequency, kHz	0.25	0.5	1	2	3	4
threshold, dB HL	-0.9	1.0	-0.4	2.8	0.8	-2.5

These values have not been adjusted to account for subject group deviations from the a-c audiometric zero, nor to account for the self-recording method used for the b-c determinations. The authors note the good agreement of their own results with those of other researchers, and with the Reference Equivalent Threshold Force Levels proposed, and subsequently adopted, for International and British Standards.

BRINKMANN and RICHTER (1983)

The authors report a series of experiments undertaken to assist in the international standardization of a b-c audiometric zero. From a pool of verified otologically normal subjects, groups of 25 subjects were used to establish Equivalent Threshold Force Levels for mastoid and forehead placements of 3 bone vibrators, each fulfilling the specifications set out in IEC 645. Subjects gave b-c thresholds by a manual bracketing method, with the non-test ear masked by a narrow band of noise with centre frequency appropriate to the test frequency. Bone-conduction thresholds were determined for each ear of each subject, at frequencies ranging from 0.125 to 8 kHz.

The results of the threshold survey are reported as mean force levels measured on a standard artificial mastoid. For presentation here, mean mastoid thresholds are given in dB relative to proposed Reference Equivalent Threshold Force Levels subsequently adopted for International and British Standards (BS 6950:1988). Values are given for all three vibrators : two of German manufacture; and the B-71 widely used in British audiometry.

bone-conduction thresholds, dB HL

frequency, kHz	0.25	0.5	1	2	3	4	6	8
model: BKH 10	8.9	-1.3	2.7	0.4	4.1	4.5	4.7	-1.7
KH 70	1.7	-3.5	-0.6	-3.0	-0.2	2.6	-0.3	-0.5
B - 71	5.0	-4.3	0.7	-1.2	1.6	2.4	4.2	-

For the most part, the values for the three bone vibrators appear randomly distributed about zero. For the lowest frequency, 0.25 kHz, a positive systematic error seems to be in evidence for all three vibrators, and for the BKH 10 in particular. However, the authors offer the opinion that a more exact specification of b-c audiometric zero is unlikely to emerge; they urge adoption of the proposed RETFL's. The proposed b-c audiometric zero was eventually adopted.

FEARN and HANSON (1983)

This paper documents a re-analysis of threshold data reported previously by HANSON and FEARN (1975) and by Fearn (1976b). The HTL's of 57 male and 19 female otologically normal subjects, age range 18-24 years, were averaged to give:

frequency, kHz	0.5	1	2	3	4	6
threshold, dB HL	5.5	0.1	-1.8	-2.6	-0.7	3.1

The mean hearing levels of otologically normal subjects, within this age range, should represent audiometric zero. At 0.5 and 6 kHz, positive hearing levels were found. The authors report levels of ambient noise, within their audiometric booth, which would produce some threshold elevation at 0.5 kHz. For 6 kHz, the authors conclude that the RETSPL is standardized at a value too low to represent true audiometric zero at this frequency.

CARTER and MURRAY (1985)

Data from 1471 young people, tested in six hearing surveys, showed systematic departures from Australian standards of normal hearing. The authors propose new values of audiometric zero for the frequencies 0.5 to 8 kHz, based upon HTL's determined by manual audiometry on groups of schoolchildren (10-12 years), university students (under 21 years), clerical workers (under 21 years) and trade apprentices (age not specified). The children were retested at mean age 18.2 years; it is this sample which provides information not previously reported by these authors, nor reviewed here.

In the first survey of the children's hearing, information was obtained on the medical and obstetric history of each subject. Children were considered "at risk", at least to some degree, if there were reports of family history of deafness, maternal rubella or medication during pregnancy, premature birth, "problems in labour or soon after birth", and blood transfusions. Other risk factors included certain childhood diseases, head injury, ear infection or earache, and perforation of the eardrum. Each subject was also examined and judged to be otologically normal or abnormal.

For the second hearing test of these subjects, approximately eight years later, the same otological examination was performed and a history obtained of events since the first examination. Audiometry was performed at six frequencies from 0.5 to 6 kHz, using a bracketing method based on 2 dB steps.

The subjects of interest here are those re-test 39 subjects judged to be otologically normal and not at risk. Data are reported as HTL's referenced to Australian audiometric zero. These values have been corrected, using data given in Robinson (1978), to be referenced to British audiometric zero, as found in BS 2497:Part 6:1988. Median HTL's are listed below.

frequency, kHz	0.5	1	2	3	4	6
threshold, dB HL	0.7	-1.9	-1.3	-0.3	-0.5	7.1

These HTLs for otologically normal young people show an apparent hearing deficit at 6 kHz. As the hearing of these subjects should define audiometric zero, it is plain that the standard value of 6 kHz is specified at too low a value.

LAWTON and ROBINSON (1986)

In the course of an investigation of tests for susceptibility to noise-induced hearing loss, hearing threshold levels were determined for 81 otologically normal young men, aged 16 to 27 years. Before audiometric testing was undertaken, each subject completed a screening process. Both ears were inspected otoscopically for any accumulation of wax, and for signs of past or current ear disease, e.g. scarring or retraction of the drum. Gross function of each ear was assessed by tuning fork tests. Each subject completed a questionnaire, seeking any history of ear disease, familial deafness or significant noise exposure which would be contraindicative of otological normality. Those subjects with clean history and no observable abnormality performed self-recording audiometry for the frequencies 0.25 to 8 kHz, first in the left, then right and last in the left again.

Considering the right and left-repeat thresholds given, the mean hearing levels are listed below, corrected by 3 dB to account for the more acute thresholds known to result from self-recording audiometry. By using this simple correction, the values listed are referenced to the audiometric zero specified in ISO 389-1975/Add.1-1983 (technically equivalent to BS 2497:Part 6:1988).

frequency, kHz	0.25	0.5	1	2	3	4	6	8
threshold, dB HL	0.8	0.5	-0.8	-0.6	0.1	0.6	2.4	4.1

It will be seen that two frequencies, 6 and 8 kHz, differ appreciably from zero. As young, otologically normal males should give thresholds which, in part, define audiometric zero, it may be concluded that the standard thresholds for 6 and 8 kHz are in error, giving normal ears an apparent hearing loss at these two frequencies.

Conclusions on Audiometric Zero

From the reviews above, it may be seen that a considerable number of research studies, large and small, may be used in the assessment of the accuracy of the internationally agreed a-c audiometric zero. These studies span the decades since the zero was first published in the mid-1960's, but all report a-c hearing levels of highly screened samples of ears within the required age range. These studies will be summarized below. In the case of the b-c audiometry, clinical practice is in a state of flux. Only within the last few years, the standards have been fundamentally altered; vibratory input is to be measured in units of force rather than acceleration. The standard specifying the construction of the artificial mastoid, used to measure the required force input, is under revision; at the time of this writing, only a printer's proof of the standard is available. As the b-c situation appears fluid at the moment, with standards yet to be published and data still coming in, an assessment would be premature. A watching brief is indicated.

Returning to the assessment of the accuracy of the a-c audiometric zero, the studies reviewed here represent an international sample of over 2500 young, healthy ears, all more-or-less highly screened for otological normality. Males and females are not equally represented in the total sample, however. Most of the studies report in terms of mean HTL at each test frequency, rather than by the use of the median. In the study of a quantity as variable as human hearing, with screening for otological normality having an influence on the sample variation, outliers might well be found in any sample, in the form of either very acute or (more likely) elevated hearing thresholds. The median, a measure of central tendency not susceptible to the influence of wild outliers in the data, would be the measure of choice. However, very few researchers have used this measure to represent their samples.

Putting aside such statistical niceties, it is possible to give an estimate of the central tendency of hearing levels for all the ears, over all the studies reviewed here. There are, however, several approaches to this exercise, each inviting a charge of invidious comparisons between researchers. The first and easiest method is to calculate a simple mean of all the means (and medians) given as individual study results. This has the effect of weighting each study as an equal contribution to knowledge; the results are given below.

mean of studies

frequency, kHz	0.25	0.5	1	2	3	4	6	8
threshold, dB HL	3.1	1.3	-0.5	-1.4	-0.1	0.9	4.3	2.3

This simple approach to the collection of study results is open to the valid criticism that small studies, employing only a few subjects (in one case, only 12 ears are reported), are given an importance equal to that of much larger studies (the largest here used over 1300 ears). To counter such a valid criticism of summary method, the obvious solution is to weight the study results in proportion to the number of ears employed in the investigation. Such an approach, seemingly more equitable, gives a mean HL over ears rather than over studies.

mean of ears

frequency, kHz	0.25	0.5	1	2	3	4	6	8
threshold, dB HL	3.2	1.4	-0.7	-1.7	0.0	0.6	4.9	2.8

This equal-ears approach might also elicit comment. "Surely, with studies involving hundreds, if not thousands of ears, the data must be of a lower standard. Surely, the screening process must have been less rigourous, in order to include such large numbers of subjects. Surely, with all those ears to be tested, the audiometry must be more like screening than research. Surely, the better way to handle all these studies is to simply mean them, giving an equal weight to each." This is the approach first tried, although not to answer the comments given.

A third approach would be to consider individual studies as exercises of metrology, fine measurement or common measurement, with differential weightings between the first two classes and zero weighting given to studies of the third sort. Such an approach would seem to be intermediary between the two tried above, and would quite probably give a representation of central tendency intermediate to the results listed above.

It should be noted that, whichever data summary is favoured, studies equal or ears equal, the underlying trend is the same. For the frequencies 0.5 to 4 kHz, the presently standardized audiometric zero is a close representation of the hearing acuity of young, healthy ears. Errors about 0 dB HL are small, and both positive and negative, and may be thought of as random errors. For the more extreme frequencies, both high and low, the errors are positive to such a degree as to attract attention. The audiometric zero for 0.25, 6 and 8 kHz is such that young, normal ears would appear to have small losses at these frequencies. At 6 kHz, a frequency important in the diagnosis of noise-induced hearing loss, the systematic error approaches 5 dB, large enough to have a marginal influence some hearing disability/handicap assessment schemes.

It would appear that the a-c audiometric zero is sufficiently in error to warrant a correction for the sake of accuracy. This idea is not new. A correction to the a-c zero has been rigourously derived, see Robinson (1978), with special attention to the RETSPL for 6 kHz, and urged upon the various standards bodies. Throughout the more recent b-c work, summarized here, care has been taken not to link the proposed b-c zero to the existing a-c zero, to avoid perpetuating inaccuracies known to exist in the a-c standard values. As yet, the idea of correcting the a-c RETSPL's defining audiometric zero has not been taken up; the small, but systematic error remains, for at least one diagnostically important test frequency.

FURTHER CONSIDERATION OF OTOLOGICAL NORMALITY

In the previous chapter, it was seen how the ISO definition of otologically normal persons influenced the standardization of audiometric zero and the relation of HTL and age. In relatively recent ISO and BSI documents, this definition has been restated, so that an otologically normal person is:

"... a person in a normal state of health who is free from all signs and symptoms of ear disease and from obstructing wax in the ear canal, and who has no history of undue exposure to noise."

Because the definition is simple, there is considerable scope for interpretation. Paradoxically, the most literal interpretation may well lead to a liberal screening process, while a more wide-ranging view of the definition gives a severe screening process, with many rejection criteria. This chapter will survey the literature in search of additional rejection criteria which bear upon otological normality.

In most of the studies reviewed in the previous chapter, a common-sense interpretation obtained. A "normal state of health" was taken to mean not suffering from the common cold or other respiratory tract infection at the time of audiometry. "Ear disease" was commonly understood to mean middle ear infection, with symptoms of pressure/ fullness and pain, and signs observable in the drum and canal. "Obstructing wax in the ear canal" was taken at face value, presumably. The last criterion, "no history of undue noise exposure", simply does not stand up under scrutiny. What does "undue" mean: undue for age; undue for sex; some but not a lot? For this criterion, reliance must be placed in the good faith and good judgment of individual researchers.

Dispersion of Hearing Threshold Levels

The minimum criteria for subject selection or screening allow considerable latitude, and must lead to some screened persons being 'more otologically normal than others'. One might infer that some samples exhibit more variability of hearing levels than would be the case if the hearing survey subjects were more tightly screened. Data exist which may be applied to this question of otologically normal variability. A number of population hearing surveys were analysed by ROBINSON and SUTTON (1978), seeking a relation between hearing thresholds and age for otologically normal persons of both sexes. (The results of this work were later incorporated in International Standard ISO 7029, giving the relation between age, sex and hearing threshold. Values extracted from this Standard may be found in the Appendix.) Using data from a number of hearing surveys, these researchers formulated the worsening of median threshold with age, for both sexes, and the widening of the hearing threshold distribution with age. At any particular age, the distribution of hearing levels about the median would be best described as a skewed Gaussian distribution, with the longer tail of the distribution extending to higher (positive) hearing thresholds. As a close approximation to this ideal, the spread of hearing thresholds at any age was represented by two half-Gaussian distributions meeting at the median, that is, the bottom half of one Gaussian distribution and the top half of another, joined together at the middle. The distribution of acute thresholds (below the median) was specified to have a smaller variance than the other half, the 'dull' thresholds greater than the median. The resulting skewness may be seen in the distribution of thresholds at 4 kHz for young people, aged 18 and 30 years, derived from the data of ISO 7029. The threshold values given below are relative to the median for 18 year old males and females, the baseline of the International Standard; the ages 18 and 30 years were chosen to represent the extremes of age for the otologically normal persons used to define audiometric zero.

Differences may be seen in the dispersion of young, normal thresholds, given here as relative thresholds over intervals of 10% of the otologically normal population. Older normals are seen to have slightly elevated and slightly more disperse thresholds in comparison to the younger normals. At a stated age, the males are seen to have the more disperse distribution of thresholds, when compared to that for females. The variability for each group is characterized by standard deviations for the acute-hearing and dull-hearing halves for the distribution. Note that, for the distributions given for each sex at each age, the dull-hearing side of the distribution has a standard deviation between 1 and 2 dB greater than that for the acute-hearing semi-Gaussian distribution. This trend continues throughout the age range of the otologically normal population represented in ISO 7029; in fact, with increasing age, the skewness toward higher thresholds becomes more extreme. (This trend may be seen in the values listed in the Appendix.)

4 kHz threshold, dB relative to that of median 18 year olds

population decile	age 18 years males	age 18 years females	age 30 year males	age 30 year females
90%	-8.6	-8.0	-7.3	-7.3
80	-5.6	-5.2	-4.5	-4.3
70	-3.5	-3.3	-1.9	-2.2
60	-1.7	-1.6	0.4	-0.4
50	0.0	0.0	2.3	1.3
40	2.1	2.0	4.7	3.4
30	4.4	4.1	7.2	5.7
20	7.0	6.6	10.2	8.3
10	10.7	10.0	14.3	12.0
	standard deviation, dB			
more acute than median	6.67	6.23	7.49	6.69
less acute than median	8.34	7.78	9.36	8.36

In simple terms, the positive skewing of the threshold distribution indicates that a small fraction of any survey population exhibits higher-than-expected thresholds. The Gaussian distribution, in this case used to model the otologically normal survey population, is essentially a description of expected random variations found in the population. The skewness of the threshold data indicates that the variations are not entirely random; some systematic error is present in the data, always working in the direction of elevated hearing thresholds. The most likely, most believable and most economical explanation of the threshold skewness is **undiscovered pathology.**

For the studies of normal threshold for audiometric zero, and of the effect of age, screening of subjects has been shown to be essentially lenient, that is, with relatively few rejection criteria stated. It must surely be the case that more stringent screening of subjects, by direct examination and history-taking, would uncover ear pathology or systemic disease. The elimination of such questionable individuals would result in a better realization of otological normality, exhibiting less threshold variability than is currently the case. To this end, a number of reviews are presented, all dealing with factors known or suspected to be associated with impaired hearing. The diseases, episodes or activities set out here might all be expected to produce hearing deficit of some degree from total down to subclinical, and must be considered as hearing risk factors.

The Reviews

LANCASTER (1951)

It was generally assumed that the Australian epidemics of deafness and other congenital defects associated with births in the years 1938-41 were new and unusual manifestations of an epidemic of rubella (German measles) occurring about that time. By examining admission records for deaf-mute schools, the author found similar associations between deaf-mute births in the years 1899, 1924 and 1925, and antecedent epidemics of rubella. The author feels that the connection is established between the rubella epidemics and the births of congenitally deaf children.

It should be noted that public health records accessible to the author did not provide evidence of the situation now known to be true: rubella in pregnant women, especially during the first trimester, carries the strong risk of a child being born hearing-impaired. The author did observe, however, the slight male prevalence in deaf births for years between the rubella epidemics. This male prevalence ties in with reports of sex-linked or sex-limited genetic hearing impairment, to be reviewed later here.

GERRARD (1952)

In a study of 360 British children in schools for the deaf, a relation was sought between sensorineural deafness and severe neonatal jaundice, Rh incompatibility and/or premature birth. Of the 33 children who had been jaundiced in infancy, this was associated with Rh iso-immunization in five. Although the numbers were small, a prevalence was indicated which was greater than that found in the population at large.

Of the deaf children surveyed, the birth weight was known in 181 instances. Thirty-three of these children weighted 5.5 pounds (2.5 kg) or less at birth, i.e. 18% were born prematurely. This prevalence contrasted with an incidence of 7% premature births in the city where the study was performed. The author found this increased incidence of premature births among deaf children to be highly significant. This incidence was linked to the observation that premature babies usually exhibit an obvious physiological jaundice, although deafness may or may not become apparent later.

SCHUKNECHT and DAVISON (1956)

Deafness and vertigo are common complaints of the patient with head injury. The authors describe three types of damage to the labyrinth, and give case histories.

Longitudinal fracture of the temporal bone of the skull will involve the middle ear, mastoid air cells, and/or external ear canal. Damage to the eardrum and ossicles, as well as the presence of blood in the middle ear and ear canal, creates a conductive hearing loss. There may well be a sensory loss component, noted below as labyrinthine concussion. As the damage to the middle ear heals, and any fluid is absorbed, the conductive hearing loss may improve. The sensory loss may be partially reversible.

Transverse fracture of the temporal bone is much more serious. The fracture, if it passes through the labyrinth, allows leakage of perilymph and/or endolymph into the middle ear. Loss of these fluids from the otic capsule usually results in complete and permanent loss of cochlear and vestibular function on the affected side.

Labyrinthine concussion may be described as a sensory hearing loss and vertigo resulting from a blow to the head without fracture of the osseous labyrinth. This injury usually results in a high frequency hearing loss.

In the experience of the authors, partial and permanent hearing loss occurs in about half of patients who incur a blow to the head of such severity as to result in unconsciousness.

KNIGHT and COLES (1960)

The hearing of Royal Navy recruits was surveyed in order to establish a reference level against which to assess the effects of noise exposure amongst naval personnel. The hearing levels determined for the screened sample were reported in terms of an American standard for audiometric zero; this standard was known at the time of writing to be considerably in error from British and European determinations of audiometric zero. For this reason, the actual hearing levels resulting from this survey will not be dealt with here; the subject selection process, however, is of interest.

One hundred and eleven male recruits to the Royal Navy were examined for inclusion in the survey., An interview/questionnaire was administered, seeking noise exposure history and any other otological, or relevant medical, conditions. Examination of each ear ensured that the canal was not obstructed by wax, and that no overt pathology was present. Of the original number, 74 of the young men, mean age 17.7 years, gave hearing threshold levels by manual audiometry, for the frequencies 0.25 to 8 kHz.

Exclusions from the original number were made for the following reasons:

1. previous noise exposure, judged without reference to the audiogram;
2. obvious deafness;
3. history of fractured skull, with ear discharge;
4. perforation of the eardrum;
5. conductive deafness and abnormal otoscopic signs; and
6. "excessive" gunfire exposure.

An upper limit was set on gunfire exposure, to be that which would cause hearing loss in normally susceptible individuals. The criteria employed, to exclude individuals for excessive gunfire exposure, were experience of:

1. 1000 rounds of Bren gun or 0.303 inch rifle, or of 0.410 inch sporting gun; or
2. 200 rounds of 40 mm Bofors gun; or
3. 50 rounds of 12 bore shotgun, or of any gun 3 inches or larger; or
4. any combination of the weapons listed above, judged to have the same effect; or
5. any gunfire exposure, if accompanied by prolonged symptoms.

To determine the influence of including young men with histories involving possible gunfire noise hazard, a group of 15 men was selected from the main group of 74; these 15 reported no gunfire exposure exceeding 7 rounds from small arms, including even the 0.22 inch rifle. Hearing level differences between the median threshold for the main group of 74 and that for the minimum-gunfire subgroup of 15 have been calculated for inclusion here; a negative value indicates that the minimum-gunfire subgroup had the more acute hearing.

frequency, kHz	0.25	0.5	1	2	3	4	6	8
difference, dB	-0.1	0.1	-1.1	-1.2	-0.6	-0.4	0.5	-3.0

The authors feel that these small differences in threshold between the main group and selected subgroup support the validity of the gunfire exclusion criteria for naval personnel. However, for present purposes, a gunfire effect of 3 dB at 8 kHz in young men (mean age

17.7 years) is worth noting. A more effective comparison would have been between the thresholds for the minimum gunfire subgroup and those for the remaining subjects, those having what the authors judge to be acceptable gunfire exposure in excess of seven rounds from small arms. A clear comparison between mutually exclusive subgroups might well have shown greater threshold differences.

DAVEY (1962)

An investigation was performed to determine the incidence of hearing loss among babies born prematurely in public hospitals in Sydney, Australia. One hundred children, all known to have weighed less than 3 pounds (approx. 1.4 kg) at birth, were each given an otological and audiometric examination at age 6 to 8 years. Specific to the investigation of hearing function and having regard to postulated causes of hearing dysfunction, enquiry was made concerning postnatal anoxia, convulsions, occurrence of jaundice, incidence of Rh-incompatibility and family history of hearing loss. Pure-tone audiometry was performed at 0.5, 1, 2 and 4 kHz; a positive response to a stimulus of 20 dB presented binaurally was considered to be normal. Of the children who failed this screen, only two were diagnosed as suffering a sensorineural hearing deficit. Five were so mentally handicapped that satisfactory screening tests could not be performed.

The author offers the opinion that the incidence of sensorineural hearing deficits in babies of very low birth weight seems to have been overestimated by other researchers. The test method used in this study would, in contrast, tend to underestimate the problem. High-frequency hearing losses were not sought, nor were unilateral losses. The negative findings could well be a function of the coarse screening process, rather than of low incidence of hearing deficit.

COLES (1963)

Two hundred and two Royal Marine recruits were surveyed audiometrically at intervals throughout their training. The principal noise hazard during training was the self-loading rifle; total noise exposure was estimated to be 300 rounds per man, with the noise of other trainees' firing also contributing.

The use of hearing protection during weapons training was variable. Of one squad showing the least usage of hearing protection, approximately one-third of the men sustained hearing losses of 25 dB or more at 3, 4 or 6 kHz, or of 30 dB at 8 kHz. These hearing losses had persisted for some three weeks between the last noise exposure and the audiometric test.

COLES and RICE (1965)

The authors describe a hearing conservation programme in the Royal Navy and Royal Marines, intended to reduce the incidence and severity of hearing loss resulting from weapons training. Specimen hearing losses were presented to illustrate the variability in noise susceptibility. One recruit, in the course of firing 350 rifle rounds, used hearing protection for 3 of 7 training sessions; a hearing loss of 40 dB at 3 and 4 kHz was found after training. Another recruit, with less use of hearing protection, showed no change in HTL's measured before and after rifle training. An instructor, who did not use hearing protection for training sessions with rifle, machine gun and mortar, showed considerable hearing loss after three years; hearing levels in both ears fell steeply from normal levels at 1.5 kHz, to levels of 80 dB or more for the frequencies 3 kHz and above.

KARMODY and SCHUKNECHT (1966)

This paper is concerned with the clinical and pathological aspects of hearing loss, which is a common symptom of congenital syphilis. The authors present their findings of a revew of 123 of their own cases seen in Massachusetts between the years 1942 and 1964; 47 of these cases exhibited hearing problems.

The pattern of hearing loss in congenital luetics shows considerable variation in the time of onset, type of hearing loss and rapidity of progression. The authors record 15 cases (32%) for which the loss was first manifested in childhood, 1-10 years, while in 22 other cases (47%) the age of onset was 25-35 years. In the adult-onset group, symptoms may begin abruptly, producing a flat sensorineural loss which may be asymmetric. The hearing loss may fluctuate, and is accompanied by episodic vertigo and tinnitus. The manifestations of congenital syphilis are similar to those of acquired syphilis, and also match those of Meniere's disease.

MAWSON (1967)

In his textbook on diseases of the ear, the author takes a particularly cautious view of tinnitus. Almost every disease or disorder of the ear may be accompanied by noises in the ear(s); local causes may be present in the external, middle and inner ear, and the eighth cranial nerve. Unilateral tinnitus is more likely to be associated with local causes, acting on one ear alone.

In addition to strictly local conditions of the ear, tinnitus may also be produced bilaterally by general disorders affecting the ears through the circulation. Such general disorders include hypertension, anaemia, leukaemia, renal disease, toxaemia, ototoxic drugs and histaminaemia associated with allergy.

It is plain that the author regards tinnitus, particularly bilateral, as an indication associated with a considerable number of more sinister disorders. "Full otological, audiological and radiological investigation of every case is required."

FLETCHER et al (1967)

Twenty-six US military personnel, hospitalized and diagnosed as having meningitis, were tested audiometrically by two methods. Conventional audiometry was performed over the frequency range 0.5 to 6 kHz. A special, high-frequency self-recording audiometer was used to determine hearing threshold levels for frequencies between 4 and 18 kHz.

The men, who mostly had not received basic weapons training, were classified into two broad groups depending upon the severity of their illness. Those men (n=15) diagnosed as having meningitis, but having not been seriously ill, exhibited high-frequency thresholds somewhat less acute than the arbitrary standard (hearing of schoolchildren) to which the audiometer had been calibrated. Those men whose hospital records indicated that they had been seriously ill with meningitis (n=11) gave high-frequency thresholds even worse by comparison. The differences in HTL between the two groups ranged from 16 to 26 dB for the frequencies 4, 6 and 8 kHz, to 55 dB at 15 kHz. Those who had been seriously ill with meningitis exhibited poorer HTL's at all frequencies from 4 kHz to 18 kHz.

WRIGHT (1968)

Over a four year period, 1963 to 1966 inclusive, 1157 patients with sensorineural hearing loss were referred to the Royal National Throat, Nose and Ear Hospital for serological tests for syphilis. Forty-six (4%) of these patients' tests proved positive. No indication is given of the degree of sensorineural hearing loss attributed to the syphilis.

Of the positive test results, 9% were attributed to yaws and 33% to adult-acquired syphilis. Congenital syphilis accounted for the remaining 58% of cases. The author notes that, in a number of the cases originally presenting with hearing loss, the cause of the loss had been completely unsuspected.

ANDERSON and WEDENBERG (1970)

A survey was undertaken to determine the hearing of young people at an age when the influence of external factors, such as noise exposure, might be presumed insignificant. Of the pupils enrolled in Stockholm schools, all those born in 1948 were screened audiometrically at age 14 years. The number of children tested was 10 778, of whom 5623 were boys and 5155 girls. These children were screened at 20 dB HL over the frequency range 0.25 to 8 kHz; 477 failed the screen and were tested further. Of the failures, 160 were due to the common cold giving a temporary hearing impairment which had normalized by the time of the second test. This left 317 with a permanent hearing impairment, of whom 51 were determined to be conductive. Of the remainder, 227 (2.1%) were diagnosed as suffering from some degree of sensorineural hearing loss. For this last group, the hearing loss could take almost any audiometric configuration, bilateral or monaural, flat or high-frequency, or dips occurring with maxima in the 1 to 2 kHz range. For the moderate sensorineural losses, particularly with deficits above 4 kHz, males were affected at a rate three times that for females.

Discussion is offered of the causes of high-frequency deficits in children, especially relating to the present sample. Cochlear sequelae of recurrent ear infections were rejected as an explanation; the expected conductive loss was not present in sufficient cases to support the observed number of cochlear deficits. Acoustic trauma or noise exposure might be considered consistent with the observed sex ratio, but such exposure was not reported in the histories. Perinatal risk factors have also been suggested as associated with hearing loss. Low birth weight was viewed by the authors as possibly connected with the cases of profound deafness. Twin births are more associated with being "small for date", and with anoxia in one twin, but this does not account for the sex ratio observed. In the end, the authors suggested a genetic factor, either sex-limited or sex-linked.

QUICK (1973)

In this review article, the author discusses the effects upon the inner ear of a number of drugs and chemicals. Of interest here are those substances which are cochleotoxic, producing tinnitus or sensorineural hearing loss. A number of antibiotics are known to produce permanent hearing loss; streptomycin, kanamycin, gentamicin and neomycin have been observed to be ototoxic. The diuretics ethacrynic acid and furosemide are also known to produce both transient and permanent hearing loss. Other drugs, such as aspirin, quinine and chloroquine, have been known to produce tinnitus and, in some few cases, permanent hearing loss. For a number of chemicals and metals, hearing loss has been reported among the neurological manifestations of toxicity. Among these substances are carbon disulphide, benzene, carbon tetrachloride, lead, mercury and arsenic; the lesion is thought to be located in the brainstem rather than the inner ear.

BALLANTYNE (1973)

Many drugs have been known to produce sensorineural hearing loss. The author presents a series of brief reviews, summarizing clinical reports and research findings on general classes of drugs known to be specifically cochleotoxic.

Salicylates, of which common aspirin is the most widely used, are known to produce reversible hearing loss; recovery may, however, be delayed or incomplete. Anti-protozoal agents used in the treatment of malaria include quinine and chloroquine, which are known to produce irreversible hearing loss. Diuretics are known to produce both transient and permanent hearing losses; ethacrynic acid and frusemide are two drugs in the latter class.

The antibiotics are by far the most important drugs known to cause hearing loss; a sensorineural loss may follow administration of practically any of the aminoglycoside antibiotics. Ototoxicity has been associated with streptomycin, dihydrostreptomycin, framycetin, kanamycin, neomycin, ristocetin, vancomycin, viomycin and gentamycin. The toxicity of these drugs may be manifested in the cochlea or the vestibular portion of the labyrinth. A patient's earliest complaint relating to drug ototoxicity is often a high-pitched tinnitus; another significant symptom is vertigo. The risk of toxicity is greatly increased by renal dysfunction; in fact, many of the ototoxic antibiotics are also nephrotoxic.

The author recommends that ototoxic drugs in general, and the aminoglycosides in particular, should be avoided altogether, unless their administration is essential to the patient's survival. This proscription applies especially in cases of renal or hepatic failure, and in the very young and very old. Ototoxic drugs should be avoided whenever possible in pregnant women.

FISCH (1973)

The author discusses the epidemiology of congenital hearing loss, defined as genetic loss, and loss due to unfavourable intrauterine or perinatal influences. Prevalence of congenital hearing loss is estimated to be 5 per 1000. From his own case records of children with congenital hearing loss, the author reports 38% with a predominantly high-frequency loss, 20% with a flat loss of moderate to severe degree; a further 20% had residual hearing only. It should be noted from these reports that the loss may affect different frequencies, and may vary in level between individuals.

In the majority of cases of congenital hearing loss, it was possible to ascribe some cause to the loss. The greatest number of cases were thought to be caused by genetic factors, maternal rubella during pregnancy, and perinatal anoxia; for these causes, the ratio of males and females affected was approximately 1:1. For another cause, blood disease of the new-born due to Rh-incompatibility, the male to female ratio was observed to be 3:1. For each of these aetiologies, congenital hearing loss is predictable and preventable, to some degree; in a proportion of cases, ranging from a quarter to a third, the observed congenital hearing loss appeared to have no discernible cause.

ZELMAN (1973)

At a US Government hospital, lifetime smoking histories were elicited by interview of one thousand consecutive patients undergoing audiometry. Those with a known cause of hearing impairment, such as head injury, ear infection or meningitis, were excluded from the series. Hearing threshold levels were determined for both air- and bone-conduction at 0.125, 0.25, 0.5, 1, 1.5, 2, 3, 4, 6, 8 and 12 kHz. The highest hearing level recorded, for air or bone in either ear, was used in the analysis. Age and sex were found to be the most important variables associated with hearing loss. The smoking variable was found to be significant at the higher frequencies.

From the total pool of 1000 subjects, 126 male smokers were then matched by age with 126 male non-smokers. At all frequencies, hearing levels were higher for the smokers. The hearing level differences between smokers and non-smokers were greatest for the higher frequencies. The author implies that the excess hearing loss resulted from smoking-related vascular insufficiency, in the form of vasospasm induced by nicotine, atherosclerotic narrowing of vessels, or thrombotic occlusions.

Note: This question was also addressed by Siegelaub et al (1974) and Drettner et al (1975).

BOSTON COLLABORATIVE DRUG SURVEILLANCE PROGRAM (1973)

This brief report gives the frequency of occurrence of drug-induced deafness in a large sample of hospital inpatients in medical wards. Members of the nursing staff recorded the details of any drugs administered, and the nature of any adverse reaction which occurred in a sample of 11 526 patients. Thirty-two developed deafness attributable to the drugs administered while in hospital; this rate was 3 per 1000 exposed. The drugs causing hearing loss were:

aspirin	11 per 1000 exposed
aminoglycoside antibiotics	13 per 1000
ethacrynic acid	12 per 1000
quinidine	3 per 1000

The adverse reactions to aspirin, ethacrynic acid and quinidine were temporary.

SURJAN et al (1973)

The authors present their analyses of audiological examinations performed on 32 397 patients in Hungary. These patients of all ages, seen between 1965 and 1971, were drawn from two localities : the capital city Budapest; and Miskolc, a centre for heavy industry.

The following table sets out the pathologies and incidences observed among the 13 902 patients seen in Budapest, and the 18 495 seen at Miskolc County Hospital.

diagnosis	Budapest %	Miskolc %
presbyacusis	22.0	17.0
noise damage	16.7	23.5
sensorineural loss, cause unknown	14.0	9.4
sequela of ear infection	11.0	11.1
chronic ear infection	10.0	14.1
trauma (unspecified)	4.1	3.7
bacterial or viral infection	3.3	3.4
otosclerosis	5.1	2.4
congenital/perinatal	3.0	2.1
ototoxic substances	2.0	1.15
Meniere's disease	0.6	0.3
sudden hearing loss	0.4	0.15
other causes	7.8	11.7

The authors also noted gender differences for several causes of hearing loss. For those patients of age greater than 65 years, there was a slight predominance of males. This finding reflects the greater degree of age-related hearing loss in males, as will be noted later in the present review document. The authors also reported a male:female ratio of 4:1 for noise-induced hearing loss, originating in the different numbers of males and females working in noise-hazardous occupations. For otosclerosis, a gender ratio of 3:7 was recorded.

It should be noted that the authors have made their analyses only on cases of hearing loss diagnosed in hospital. The 32 397 cases are self-selected from an estimated population slightly in excess of 10 million. There is the possibility of further cases of hearing loss seen by general practitioners, or not seen at all. The reported incidences of various hearing pathologies, although drawn from the Hungarian population, must surely give some indication of the approximate ranking of these same pathologies in the British population.

GJAEVENES et al (1974)

The authors performed an audiometry survey among schoolchildren to estimate the incidence of hearing loss caused by the impulsive noise of fireworks. Over several days before a national holiday, audiometric screening was performed in a number of Norwegian schools. The sample comprised 735 boys and 56 girls, aged 12-15 years, who gave positive responses to signals of 10 dB HL at 2, 3, 4 and 6 kHz. Within one week of the national holiday, celebrated with fireworks, the subjects were retested. Fifty-four of the children showed a threshold degradation of at least 15 dB at one or more of the test frequencies.

Of the children showing an immediate hearing loss, five of the boys showed a loss of at least 40 dB remaining four months after their exposure to the noise of fireworks. All of these sensorineural losses showed audiograms which fell very steeply from normal at 4 kHz; most had the maximum loss at approximately 6 kHz. The authors estimated the incidence of permanent hearing loss to be 0.7% among those children who used fireworks to celebrate the national holiday.

NADOL (1978)

A retrospective study was performed of cases of hearing loss following meningitis. A review of admission diagnoses at a Massachusetts hospital for the years 1962 to 1975 yielded 547 cases of acute meningitis. Of this total, 236 were of bacterial origin, 304 aseptic or viral, and 7 fungal; hearing loss was a common sequel of bacterial meningitis, as may be seen in the data below.

<u>age 0-2½</u>

survived	n = 100	
died	5	
hearing loss	5	(5% of survivors)

<u>age 2½ and over, including adults</u>

survived	110	
died	21	
hearing loss	23	(21% of survivors)

For the cases of bacterial meningitis showing a hearing loss, the loss was sensorineural and bilateral in 77% of the cases, and sensorineural unilateral in 23%. In about 70% of cases, the loss was partial; of these, most patients had some recovery of hearing. In contrast, if all hearing function was lost, no recovery occurred.

TAYLOR and IRWIN (1978)

In reviewing the relationship between sensorineural hearing loss and diabetes mellitus, the authors found widely varying estimates of the incidence of diabetic hearing loss. There also seemed to be differing estimates of the relationship between hearing loss and other aspects of the disease, such as severity and duration of the diabetes, age, sex ratio, and blood pressure. However, the authors seemed satisfied that audiological changes associated with diabetes are due to widespread changes in the vascular system. These hypotheses are not pursued in the hearing survey reported in this paper.

Hearing threshold levels were determined at the octave frequencies from 0.125 to 8 kHz, for 77 subjects aged 15 to 66 years. The 38 diabetics, who were all dependent upon insulin therapy, were drawn from consecutive outpatient clinic sessions. The sample selection favoured patients under 50 years, in an attempt to minimize the effects of presbyacusis upon the survey thresholds. The control group of 39 subjects was selected to follow closely the age and sex composition of the diabetic group; the provenance of the control group is not stated.

Given below are the mean thresholds and standard deviations for the two test groups.

descriptive statistics, dB

frequency, kHz		0.125	0.25	0.5	1	2	4	8
diabetics,	mean	13.8	11.4	11.6	7.5	7.8	6.6	8.3
	s.d.	8.8	10.3	9.4	9.2	9.9	11.5	15.9
controls,	mean	4.9	4.1	5.2	2.2	1.7	2.5	4.7
	s.d.	6.5	6.4	6.0	5.5	6.5	9.1	12.7

Inspection of these values shows that the diabetics have less acute thresholds at each frequency. Analysis of variance showed that these differences across frequency were great enough to conclude that the two groups are drawn from different populations. For this sample of diabetics, the females were shown to have significantly higher thresholds than the males.

The data from these samples of control and diabetic subjects were also analyzed for the incidence of hearing impairment, using methods reported by other authors. For the diabetics, the incidence of impairment ranged from 0% to 44%. It was evident to the authors that the wide variation in incidence quoted in the literature was due entirely to computational differences, involving the setting of absolute limits of normality, or the use of group means plus a set increment or plus a specified proportion of the standard deviation. The authors appear to counsel that incidence rates are so pliable as to be useless.

It should also be noted that the study under review is not without its own shortcomings. For relatively small samples of diabetics and unknown controls, the numbers within each age range must be smaller still. With the hearing level differences between groups being on the order of the hearing deficits accruing to each subgroup of increasing age, group means are not particularly informative. One or two aberrant individuals within a group can have a large influence upon the mean; within an age group, the effect may be larger still. The authors would have spent their time more profitably by identifying and testing 39 more diabetics rather than 39 controls. The considerably more potent diabetic group statistics could easily have been compared against table values of normal hearing against age.

GIBBIN (1979)

On the basis of numerous research reports of the relation between diabetes mellitus and sensorineural hearing loss, the author performed a further study to test the relationship. In the event of a positive correlation between diabetes and deafness, the study would attempt to determine the site of the lesion, viz. cochlear or retrocochlear.

Fifty diabetics were selected at random to act as subjects; none were admitted to the survey if the history revealed noise exposure, use of ototoxic drugs, middle ear disease or family history of deafness. Fifty non-diabetics, age and sex matched to the diabetics, composed the control group. The following hearing tests were performed on the members of each group: pure-tone audiometry at the octave frequencies from 0.25 to 4 kHz; tone decay tests; and speech discrimination tests. With the exception of one frequency used for the tone decay tests, there were no significant differences between the audiological results for the diabetics and those for the control subjects.

ABRAMOVICH et al (1979)

During the period 1966-72, 272 infants of birth weight 1550 grams or less were admitted to the neonatal intensive care unit of a London teaching hospital; 48% survived. The hearing of 111 of these survivors was tested 4 to 12 years later. Ten children (9%) were found to have a sensorineural hearing loss of unstated degree. Twenty-one of the children (19%) had otitis media with a mean hearing loss of 24 dB.

GRIFFITHS (1979)

A study was undertaken to examine the incidence of otoneurological abnormalities associated with minor head injuries. From a hospital casualty department, head injury patients were selected for inclusion in the study on the bases of the following criteria:

1. a history of post-traumatic amnesia of less than 24 hours;
2. no radiological evidence of skull fracture;
3. evidence of direct injury to the skull; and
4. no evidence of previous ear disease or trauma.

A total of 84 patients were selected for the study. All patients gave pure-tone hearing threshold levels, presumably after stabilization of the head injury. All patients were reviewed after three months; those with residual hearing loss or vertiginous symptoms were reviewed again at 6 months. An age-matched control group of 40 subjects was selected from relatives of the head-injury patients.

A very high proportion of the head injury cases exhibited a sensorineural hearing loss on first examination; after six months, 14% still had a hearing loss. Frontal injuries resulted in a relatively low incidence of hearing loss, compared to that from a temporal blow. The incidence of hearing loss and vertigo following head injury was very much more than anticipated by the author.

ROBINSON et al (1979)

A determination of the normal threshold of hearing by air-conduction was made using self-recording audiometry for the audiometric frequencies 0.5 to 6 kHz. Special attention was given to the selection of otologically normal subjects in the age range 18 to 30 years. Audiometry and otological selection of the 108 subjects was performed independently, to avoid one measurement series influencing the other in that part of the study seeking a relation between hearing thresholds and deviations from otological normality.

A systematic procedure was employed to rank subjects with respect to departure from the strict definition of otological normality. Before attending for audiometry, each subject completed a questionnaire to define his or her noise exposure history and to uncover episodes or conditions affecting otological health. Before giving hearing thresholds, each subject was examined otoscopically and by the use of tuning forks. Findings on examination were given more weight than symptoms or questionnaire reports.

Each subject was graded on the basis of the questionnaire responses and findings on examination, in order to avoid an arbitrary decision to accept or reject from the subject pool. Each subject was assigned an Otological Abnormality Score, being the sum of points charged against the following conditions:

1. history of occupational noise exposure
2. exposure to gunfire noise
3. exposure to the noise of explosions
4. history of noisy recreation
5. history of ear discharge
6. tinnitus (according to severity or persistence)
7. episode(s) of unconsciousness
8. family history of hearing disorder
9. use of ototoxic drugs
10. history of general "ear trouble"
11. scarring of eardrum(s)
12. retraction of eardrum(s)

13. unfavourable Rinne test
14. unfavourable Bing test
15. diplacusis

Anyone with a history of ear or mastoid surgery, or ruptured eardrum, was rejected outright. Some subjects presented the following temporary conditions:

1. wax in the external canal(s)
2. current upper respiratory tract infection
3. current ear discharge

These individuals were admitted to the subject sample in order to gauge the relative importance of these conditions, by retest on recovery or after wax removal.

So far as possible, the audiometry was performed in accordance with the method described in the discussion documents reviewed as HEALTH AND SAFETY EXECUTIVE WORKING GROUP ON AUDIOMETRY (1978). Subjects first performed a brief practice session 0.5 kHz in the left ear. Each subject then gave threshold tracings for 0.5, 1, 2, 3, 4 and 6 kHz, first in the left ear, then right and last, a left ear repeat. Thresholds were read from the right and left-repeat tracings. The tracings were analysed independently by two readers, following the HSE recommended procedure.

Results were given as HTL's against frequency, averaged over various subsets of the subject pool. Given below are mean HTL's for two subject samples, those fulfilling the most rigorous definition of otological normality, with no unfavourable history or clinical findings whatever, and for all subjects free of wax and current respiratory tract infection but without regard to history or findings. The values listed have been adjusted to account for known differences between thresholds determined by self-recording and manual audiometric methods.

frequency, kHz	0.5	1	2	3	4	6
mean HTL, dB						
otologically normal (n=11)	1.7	-1.3	-0.8	-1.1	2.0	3.4
all subjects free of wax and infection (n=62)	3.7	1.0	1.1	2.4	4.7	8.2

With the exception of the exclusions for earwax and respiratory tract infections, there was a smooth progression of mean HL with increasing deviation from the strict ISO definition of otological normality. No break point was found in the relation of HTL to abnormality score; the authors concluded that no natural cut-off point exists which would allow a relaxation of the most strict definition of otological normality.

AMERICAN COUNCIL OF OTOLARYNGOLOGY (1979)

The Medical Aspects of Noise Committee of the American Council of Otolaryngology has formulated criteria for medical referrals, to be applied within occupational hearing conservation programmes. Criteria dealing with hearing levels set out boundary values, or fences, for average hearing level at 0.5, 1, 2 and 3 kHz (without reference to age), for differences in average hearing levels between the worse and better ears, and for hearing level changes between the current audiogram and one taken not more than two years previously.

If a worker has any of the medical problems or conditions listed below, that person should be referred to specialist advice, and treatment if appropriate.

1. presence and persistence of ear pain
2. ear discharge
3. dizziness
4. severe, persistent tinnitus
5. sudden or fluctuating hearing impairment
6. rapid hearing loss
7. feeling of fullness or discomfort in the ear
8. accumulation of cerumen
9. foreign body in the ear canal

The presence of any of these conditions, or history of such within the preceding 12 months, is by implication a serious deviation from otological normality.

HAZELL (1980)

Otological, audiometric and psychometric evaluations were performed on 200 patients whose primary complaint had been tinnitus.

A history of noise exposure was elicited in 55% of the group; 11% reported use of ototoxic drugs; 35% had a family history of tinnitus or deafness. In spite of these possibilities, no firm diagnosis could be made in 58% of the cases. Of the 200 tinnitus sufferers, 30% had normal hearing, what the author defined as an average threshold less than 30 dB over the six audiometric frequencies from 0.250 to 8 kHz.

PAPARELLA et al (1980)

Considering the hypothesis that chronic otitis media can result in inner ear pathology, the authors reviewed the clinical and audiological records of 279 ears, representing 232 patients, exhibiting both conditions. Sensorineural hearing loss was diagnosed if bone-conduction HTL's were elevated from normal; all possible causes were eliminated, save the long-standing middle ear disease.

Mean b-c thresholds at 0.5, 1, 2 and 4 kHz are presented, grouped by duration of middle ear disease. These data appear to show that the thresholds deteriorate as the disease persists, with the worst thresholds for durations greater than 30 years. However, no attempt is made to separate the confounded variables of age and duration of disease.

The confounding of variables is continued with the presentation of increasing b-c thresholds, averaged for patients in the ranges 40-49, 50-59 and greater than 60 years. The data might simply be interpreted as showing that sensorineural hearing loss increases with the age of the patient suffering chronic otitis media.

From the large subject sample, the authors present little which may be taken at face value. For 32 patients, mean b-c thresholds are contrasted for the diseased and unaffected ears. For these patients aged 20 to 50 years and acting as their own controls, the diseased ears showed the worse thresholds, by approximately 3, 7, 11 and 15 dB at 0.5, 1, 2 and 4 kHz respectively. This meagre subgroup is the only direct evidence offered in support of the authors' hypothesis, that long-lasting middle ear disease can cause sensorineural hearing loss.

This line of argument takes no account of known artefacts of b-c measurements, reported by CARHART (1950), GUNDERSEN (1973) and Ginsberg (1978). When such adjustments are applied to the authors' data, no support remains for the hypothesis that otitis media can cause inner ear pathology.

SWAN et al (1980)

A study was performed to document the pure-tone thresholds of individuals who had suffered a minor head injury, in comparison to a control group. Hearing loss has been reported as a common sequel to head injury, but the authors' clinical experience did not suggest a high incidence.

One hundred and thirty individuals with minor head injury, of no stated severity, were compared with 87 individuals with injuries other than to the head. When analysed according to age and sex, there was no difference between groups for air-conduction thresholds, measured within 24 hours of injury, at any frequency. There were complaints of hearing loss and/or tinnitus in each group.

Of the patients with somewhat elevated hearing levels, about half of each group were retested two to four weeks following injury. Again, there was no difference in auditory threshold, when analysed by age and sex, between those receiving an injury to the head or to some other part of the body. It is difficult to reconcile this negative finding with the positive observations reported elsewhere in this section.

WRIGHT (1980)

In this study, an unstated number of cochleae were examined post-mortem, from patients who had received a loop diuretic with or without the addition of an aminoglycoside antibiotic; these two classes of drugs are known to be ototoxic. Cochleae from controls were also examined by scanning electron microscopy; these tissue samples were from patients who had not received any ototoxic drug before death.

In the diuretic-only group of tissue samples, swelling of the stria vascularis was noted, but only occasionally. In the diuretic-plus-aminoglycoside group, more severe swelling was noted, with "fusion and clumping" of the cilia of the hair cells. Collapse of these cilia, or hairs which give the sensory cells their common name, was also seen in distinct regions of the cochlea, indicating a significant departure from normality. This cell damage was presumed due to the drugs administered before the death of each patient supplying tissue samples.

BROWNING and DAVIS (1980)

A study was undertaken to estimate the incidence and character of hearing disorders in the adult British population. A total of 6804 questionnaires were sent to a random sample taken from the electoral role. From the respondents, 280 selected individuals attended for audiological investigation.

A hearing disorder was defined as an average threshold greater than 25 dB HL for the frequencies 0.5, 1, 2 and 4 kHz. The results from the 280 individuals tested suggest that 19% of the population have a hearing disorder in the better-hearing ear and 34% in the poorer-hearing ear. Of the ears with a disorder, sensorineural loss is found in 67%, conductive in 18%, and mixed loss in 15%. Excluding age, the main factor associated with sensorineural hearing loss was noise exposure (36%); with conductive loss, the main factor was diagnosed to be chronic otitis media.

These results, from a pilot study for the National Study of Hearing by the MRC Institute of Hearing Research, suggest that incidence of hearing loss in the adult British population is higher than previously estimated. (A later report, by Davis (1989) on the National Study of Hearing offered the overall conclusion "... the prevalence of hearing impairment is not greatly associated with noise exposure, sex or occupational group, but predominantly with age".)

BAUCH (1981)

Single-notch and double-notch sensorineural hearing losses were observed in 27 adult patients. A notch was defined as a hearing threshold level at any frequency, at least 15 dB greater than the hearing level determined an octave above and below. Single notches were observed at 1 and 2 kHz; double notches were observed at 0.5 and 4 kHz, and at 1 and 4 kHz.

All patients denied a history of noise exposure, but did report at least one episode of head trauma. The laterality and degree of hearing loss was not correlated with the site and degree of head trauma, or with post-traumatic signs and symptoms such as unconsciousness, tinnitus or dizziness.

The author cautions that not all individuals suffering head trauma, concussion or skull fracture will have a notched audiometric configuration as a consequence of their injuries. However, when an individual is found to have a notched audiogram, the possibility of head trauma, as well as noise exposure, should be pursued in the case history.

AXELSSON and LINDGREN (1981)

The authors note that live popular music is consistently presented at sound levels which could damage the hearing. If hearing impairment does occur, the authors suggest that it should be most common in those with the highest exposure, the musicians themselves.

Pure-tone audiograms were obtained from 83 individuals in the popular music business : 69 musicians; 4 disc-jockeys; 4 managers; and 6 sound technicians. Thirteen cases were eliminated for sensori-neural hearing loss unassociated with music (age, congenital hearing loss, and previous noisy occupations). Of the remainder, 11 individuals exhibited a mean HL at 3, 4, 6 and 8 kHz greater than 20 dB, in at least one ear. A positive finding in 11 of 70 suitable cases is not compelling evidence in support of the hypothesis that exposure to popular music can cause hearing damage.

MRC INSTITUTE OF HEARING RESEARCH (1981)

The Institute of Hearing Research has responsibility for the investigation of the prevalence, characteristics and determinants of hearing problems and tinnitus in the adult population of the UK. The results of a pilot study, in preparation for a major, long-term National Study of Hearing, are reported in this document.

A questionnaire on hearing difficulties and tinnitus was sent to over 6800 people drawn from the electoral registers of Cardiff, Glasgow, Nottingham and Southampton. Of the respondents, 272 attended for clinical assessments and audiometric tests, among which were conventional air- and bone-conduction threshold determinations.

Taking a criterion of an average hearing level of 25 dB over 0.5, 1, 2 and 4 kHz in the better ear, an estimate is made that 19.9 ± 4.4% of UK adults have some hearing difficulty. About 17% reported an experience of tinnitus that was more than transitory or temporary noise-induced. The relation between questionnaire reports and audiometric results are given below:

report	better-ear average HL, dB	worse-ear average HL, dB
normal	11	15
tinnitus	17	25
hearing impair.	26	33
hear.imp. + tinn.	40	53

It is noted that, in both the normal and impaired groups, the average hearing level for both better and worse ears increases markedly when there is a report of past or present tinnitus. This is interpreted as indicating that "tinnitus is an early sign of auditory disorder in which the associated hearing loss is still subclinical".

AXELSSON et al (1981)

A hearing survey was conducted among 538 males aged 17 to 20 years, all pupils attending vocational classes. Manual audiometry was performed for the frequencies 0.25 to 8 kHz. The survey results showed that 84% of the young men had thresholds less than or equal to 20 dB HL at all frequencies. A unilateral hearing loss was found in

10% of the subjects. Bilateral losses, both symmetrical and asymmetrical, were found in 6% of the subjects. In a number of the hearing loss subjects, the audiogram assumed a high-frequency dip configuration, which the authors took to indicate noise damage in spite of the youth of the subjects. No explanation was offered for the unilateral or asymmetrical losses; hearing loss due to infection or genetic factors was not considered.

RYTZNER and RYTZNER (1981)

A hearing survey was performed to determine the prevalence and nature of the 4 kHz notched hearing loss in schoolchildren, presupposing noise as the cause. Pure-tone screening audiometry, with special attention paid to 4 kHz, was administered to 14 391 pupils aged 7, 10 and 13 years. A screening failure was noted if no response was elicited at 20 dB HL, relative to ISO audiometric zero (equivalent to British audiometric zero). Children who failed at 2 or more frequencies went on to give a full audiogram, as did those who failed the screening at 4 kHz alone. The children with a 4 kHz dip greater than 20 dB HL were also questioned about possible noise exposure.

The screening failures (n=331, 2.3%) at 4 kHz are listed below; as percentage of children at each age:

age	total	screening failures, %				
yr	number	boys	girls	unilat.	bilat.	total
7	4599	2.0	1.0	1.3	0.4	1.7
10	4655	2.7	1.2	1.3	0.6	2.0
13	5137	4.9	1.5	2.1	1.0	3.2

Out of 331 screening failures, 210 of the children reported exposure to loud noise. The sources were, in decreasing order of prevalence: tractor; other motor vehicle; fire arms; fireworks; machinery; factory noise; and musical instruments.

The authors conclude that the 4 kHz losses, observed to be greater than 20 dB HL, were caused by noise. The high proportion of unilateral hearing losses is not explained; no probable cause is offered for the subgroup, approximately one-third of the screening failures, from whom there was no report of noise exposure. The hearing losses are documented, the cause(s) of the losses would appear to remain obscure.

KLOCKHOFF and LYTTKENS (1982)

The authors report a sample of thirty children exhibiting hearing losses typical of noise damage, but without noise exposure. The children had a mean age of 14 years; 25 were boys, 5 girls. Among this sample, there were 51 ears with a "noise notch" sensorineural loss greater than 20 dB HL. The median loss was 50 dB HL at or around 4 kHz; losses were symmetrical, asymmetrical and unilateral.

Although the audiograms exhibited the notch typical of noise damage, no noise exposure history could be elicited by questioning of children or parents. Questions were also asked concerning pregnancy, birth, any head injuries, use of ototoxic antibiotics and any relevant disease episodes; no positive reports were given.

The parents were questioned concerning the presence of significant hearing impairments of uncertain origin in themselves, their siblings and cousins, and in the child's grandparents and their siblings and cousins. Known risk factors and advanced age were excluded. Family deafness was present for 76% of the notch-loss children, as opposed to 17% for a control sample of normally-hearing children similarly questioned. The authors concluded that a genetic disposition was responsible for the notched, high-frequency hearing losses observed in this sample of children.

GOODWIN (1983)

The author discusses fractures of the temporal bone, containing the middle and inner ears. Patterns of injury are outlined, with typical histories of each class of head trauma.

Approximately 70 to 80% of temporal bone fractures are longitudinal, usually resulting from a blow to the temporal or parietal region of the skull. The cardinal symptoms are bloody discharge from the ear canal, and conductive hearing loss. This loss is secondary to laceration of the eardrum and/or ossicular damage, resulting from the fracture passing through the middle ear. Mild sensorineural loss may also occur as a result of cochlear concussion; because the fracture does not involve the inner ear, some improvement may be expected for the sensorineural loss.

The remainder of temporal bone fractures may be classified as transverse. Here, the line of the fracture passes through the cochlea and/or balance organs, or through the eighth cranial nerve which serves these organs. Hearing loss is sensorineural and permanent.

In actual practice, classification of temporal bone trauma cannot be purely longitudinal or purely transverse. Most cases are classified on whether the middle or inner ear is involved. In any case, definitive treatment of the ear injury must be delayed until the life-threatening head trauma has been resolved.

VAN DEN WIJNGAART (1983)

The author reports how a hereditary, progressive sensorineural hearing impairment has affected 105 members of a Dutch family. The hearing loss is expressed as a step-shaped audiogram. The age of onset is between 5 and 15 years; the loss is symmetrical.

In the first stage, the loss takes the form of a high-frequency roll-off in the audiogram. A high-frequency hearing loss plateau then develops. As the impairment worsens, the high-frequency plateau degrades to higher hearing levels, giving a precipitous loss from 1 or 2 kHz; the lower frequencies are normal. Finally, the low frequencies deteriorate evenly, with similar high-frequency deterioration. In its middle and later stages, the developing hereditary loss follows a symmetrical course not unlike what would be expected for advanced noise-induced hearing loss.

This family has been studied over a number of years; see Huizing et al (1966a, 1966b and 1972).

CAHANI et al (1983)

A study was conducted to compare the pitch of the tinnitus reported by two groups of subjects. Members of the first group, 27 in all, reported exposure to loud noise and exhibited high-frequency, sensorineural hearing loss which the investigators considered consistent with noise damage to the hearing. The second group, numbering 29, had suffered noise exposure, but had normal hearing, that being defined as HTL's not exceeding 20 dB at any frequency. The 56 subjects were all male in the age range 19-44 years. No indications of noise exposure history were given for either subject group.

The subjects were placed in the appropriate group on the bases of pure-tone audiometric tests performed by air- and bone-conduction. The tinnitus frequency match was performed using pure tones of standard audiometric frequencies, including half-octaves. The tones were presented monaurally, in ascending order of frequency, at 10 dB above threshold. The subject was instructed to indicate whether the test tone had a pitch higher, lower or similar to that of his own tinnitus. The matching procedure was performed twice.

For the subjects with noise-damaged hearing, 89% matched their tinnitus frequency to tones of frequency 2 kHz or higher. Of the normal subjects, 79% indicated tinnitus frequencies of 1.5 kHz or less. The authors suggest that the tinnitus of subjects in the noise-damaged and normal-hearing groups is generated by different processes.

DAVIS (1983)

A report is made of the age-related aspects of hearing disorders in the UK. The conclusions are drawn from data collected in a pilot study for the National Study of Hearing, conducted by the MRC Institute of Hearing Research.

A postal questionnaire was sent to a random sample (n>6800) drawn from the electoral registers of four British cities. Of the questionnaire respondents, 65% reported no hearing disorder. Of the remaining 35%, tinnitus only was reported by 9%, hearing problem only by 17%, with 9% reporting both tinnitus and hearing problem.

Of the questionnaire respondents, 272 attended for otological examination and audiometric tests. Using a criterion of 25 dB HL for the better ear average at 0.5, 1, 2 and 4 kHz, it was projected from this sample that the proportion of the UK population with a hearing problem would be 19.9% with a 0.95 confidence interval of ± 4.4%. The audiological examination results were further used to project classification of hearing problems by better and worse ears. For the percentages listed below, "sensorineural" is defined as a value for the four-frequency average hearing level equal to or greater than 25 dB HL, with an air-bone gap less than 15 dB.

hearing classification, %	better ear	worse ear
normal	81.0	66.0
sensorineural	15.5	20.0
conductive	1.5	8.0
mixed (sens. + cond.)	2.0	6.0

From these data, it may clearly be seen that a significant proportion, 34%, of UK adults have a hearing deficit in at least one ear.

GATEHOUSE (1984)

Auditory function was studied in 96 individuals who had suffered a head injury of such severity as to result in unconsciousness or coma lasting longer than 6 hours. In these patients, 59 males and 37 females, evaluations were made of peripheral function (by pure-tone audiometry, tone decay, acoustic impedance, speech audiometry, etc.) and central function (by binaural speech audiometry, interaction of brainstem electric response, etc.). Thirty-nine normal hearing individuals served as controls.

When peripheral auditory function of the head injury cases was compared to that of the matched normal group, the expected hearing deficits were found. These deficits were presumed due to temporal bone fracture and damage to the ossicular chain, cochlea and eighth nerve. Forty of the head injuries, however, showed normal peripheral function. Eighteen of these 40 showed abnormal central auditory function, compared to only 2 among the control group of 39. The implication is that, for any serious head injury, there is a strong possibility of some audiological consequence, either peripheral or central.

BALDWIN et al (1985)

At an American children's hospital, a total of 54 patients were diagnosed as suffering from generalized meningitis, during the year 1983. Of these patients known to be at risk of sensorineural hearing loss, 38 of the 54 had meningitis attributed to the micro-organism **Haemophilus influenza**; from this subgroup, 9 were found to have some degree of sensorineural hearing loss. This finding prompted the authors' strong recommendations:

1. All children with a diagnosis of bacterial meningitis should be referred for audiological evaluation prior to discharge from hospital.
2. Any child who is later discovered to have slipped through this net should be referred for audiological evaluation, even if the examining physician forms the impression that the child does not have a hearing impairment. Such a child may have a mild hearing loss, of such a degree as to interfere with his education, or a subtle high-frequency loss which may disturb the normal acquisition of speech and language skills.

It is clear that the authors regard bacterial meningitis as a disease carrying a high risk of sensorineural hearing loss.

MRC INSTITUTE OF HEARING RESEARCH (1986)

This paper presents the main findings of a literature review of damage to hearing arising from leisure noise; see MRC Institute of Hearing Research (1985). There is an extensive body of literature in this area, dealing with amplified music, firearms, fireworks, noisy toys, sports cars and motorcycles. The research was found frequently to be poor in design, method and reporting, and of limited value for the purpose of estimating the hazard to the whole population. To give such an estimate, it is required by the authors that research accurately estimate the number of exposed persons, establish representative sound levels and patterns/durations of exposures, and show the results of properly conducted field audiometry to evaluate the modest effects of short-term exposures.

In spite of the shortcomings of the literature reviewed, it was concluded that the population hazard from non-occupational noise is not great, but it may not be altogether discounted. However, for present purposes, the concern is not for population hazard but rather individual risk. "For the individual, worst cases of exposure to discotheque and personal cassette player noise represent real risks, as do some other non-occupational noise exposures, e.g. shooting without proper hearing protection."

KLOCKHOFF et al (1986)

Screening audiometry was performed on 38 294 young men conscripted into the Swedish armed forces over the period 1976-79. The conscripts, typically 20 years old, gave thresholds at 0.5, 1, 2, 3, 4 and 6 kHz, on reporting for and discharge from basic training which usually lasted 245 days.

On reporting for basic training, 71% of the conscripts were found to have "normal" hearing, that being threshold at any frequency not exceeding 20 dB HL. The remaining 29% of the young, typical/unselected conscripts had "defective" hearing, with a threshold exceeding 20 dB HL at one or more frequencies in either ear, with high frequency, sensorineural loss predominating. On discharge, 3% (860 of 27 309) of the normal-on-entry subjects had suffered a high-frequency deterioration. Of the defective-on-entry subjects, 9% (1031 of 10 985) had suffered high-frequency hearing deterioration. The authors offer the interpretation that, in relation to the normal sub-group in this unselected or random sample, the defective sub-group is more at risk of further hearing loss. For present purposes, the substantial proportion of young men with "defective" hearing indicates the population prevalence of hearing 'risk factors'.

YLIKOSKI (1987)

Audiometric configurations were analyzed for 361 young Finnish military conscripts who suffered hearing damage as a result of their military service. These young men were sampled from the worst cases of damage, resulting in compensation claims in respect of national service over the period 1970 to 1984.

The hearing damage, presumably from exposure to the noise of side arms and heavy weapons, was determined by audiometry performed at 0.25, 0.5, 1, 2, 4, 6 and 8 kHz. The results are reported as percentages exhibiting a particular audiometric configuration, as listed:

HTL at 1 kHz normal with notch at 2, 4 kHz or 8 kHz dip	8%
HTL at 2 kHz normal with notch at 4, 6 kHz or 8 kHz dip	48%
HTL at 4 kHz normal with 6 kHz notch or 8 kHz dip	19%
8 kHz dip only	6%
loss involving lower frequencies	17%
difficult to classify uniquely	2%

These results indicate that exposure to weapons fire can result in a wide range of audiometry configurations. In this survey of severe damage, hearing losses took the form of distinct notches, high frequency slopes, and flat losses, in fact all of the typical sensorineural audiogram configurations.

BELLMAN (1987)

It is recognized, in the U.K. at least, that the earlier the rehabilitation of a hearing-impaired person begins, the more effective that rehabilitation becomes. For the purpose of early identification of hearing-impaired individuals, the author discusses a considerable number of conditions, events and risk factors associated with hearing deficit. Many of these are of interest here.

1. Tinnitus frequently co-exists with hearing impairment, and may be a symptom of local or systemic disease; it may be a hearing problem in its own right.
2. Vestibular disorder indicates disease or damage within the labyrinth, which may also affect the hearing organ.
3. Genetic hearing loss may be congenital, or it may be delayed and manifest itself at any period of life from infancy to old age.
4. Noise trauma may result from occupational noise exposure; consideration should also be given to recreational or social exposure, as with loud music, sport shooting, power tools and motorcycles.
5. Dysbarisms, the effect of changes in atmospheric pressure, may cause hearing problems in several ways. Reduced pressure, as encountered while flying, may cause middle ear problems, which are usually short-lived. Raised pressure, as with divers, may also result in middle ear disorders; however, a more serious problem in divers is decompression sickness, which can lead to local necroses in the cochlea and brainstem, due to gas bubbles in the tissues.
6. Maternal infection by rubella, or German measles, has only relatively recently been associated with congenital defects, one of which is deafness. Foetuses infected in the first trimester of pregnancy exhibit multiple handicaps, including deafness. Of those infected at a later stage of intra-uterine development, approximately half have a hearing loss.
7. Congenital syphilis, although no longer common in the U.K., will result in approximately one-third of those affected developing a hearing loss in childhood or early adult life.

8. The incidence of hearing loss in pre-term, very-low-birth-weight infants has been estimated to be 5%. This incidence is not likely to fall substantially while efforts are made for the survival of increasingly premature infants.
9. Deafness has been associated indirectly with severe jaundice in infants, and to Rh-incompatibility between mother and unborn child. Improvements in therapy have made these conditions less common in the developed countries.
10. Several relatively common infections are known to cause sensori-neural hearing loss, among these are meningitis, measles and mumps. Ear infections may result in some degree of conductive hearing loss.
11. In adults, a number of systemic diseases and disorders have been associated with hearing loss; among these are diabetes mellitus, blood viscosity disorders, atherosclerosis and renal disease.
12. Damage to hearing and vestibular function may be produced as a side effect by a wide range of drugs. A number of drugs are listed, the majority of which have been noted previously here. However, a new aspect of ototoxicity is aired: the use of aminoglycoside antibiotics and diuretics together, as might occur in cases of renal disease, should be avoided as drugs from the two groups will potentiate their mutual side effects.

The author treats these points, and others not included here, as indicators for early rehabilitation of hearing impairment. For present purposes, these items may also be thought of as indicators of risk to otological normality. Report of any of these risk factors provides a possible cause for hearing deficit in the individual.

COLES (1987)

Two systems are explained to assist the clinician in classification and management of tinnitus. The system presented here, classification by site of auditory dysfunction, is the more informative, allowing the reader to separate types of tinnitus into benign and pathological.

1. Physiological ... normal body sounds apparently arising within the head, circulatory hum, muscle tremor
2. Pathophysiological ... temporary
   - A. Spontaneous ... a whistle-like sound lasting only a few seconds, a common experience
   - B. Noise-induced ... supplementary to dullness of hearing or TTS after exposure to loud noise
   - C. Drug-induced ... most commonly experienced with use of alcohol or aspirin
   - D. Toxaemic states
3. Pathological ... associated with a definite disorder
   - A. Extra-auditory ... muscular, vascular and respiratory sounds
   - B. Conductive ... revelation of tinnitus by the attenuation of ambient noise by a conductive hearing loss
   - C. Sensorineural
     - i. Sensory ... associated with cochlear dysfunction such as presbyacusis, noise-induced hearing loss, vascular deficiency
     - ii. Peripheral neural ... unilateral tinnitus may indicate acoustic neuroma
     - iii. Central neural ... in the central auditory pathways, possibly coincident with cerebrovascular accident
   - D. "Reflex (non-auditory)" ... associated with injury or dysfunction in the jaw joint or cervical vertebrae, also with spasms of associated muscles
   - E. Psychological
     - i. Hallucinations ... "hearing of voices", "likely to be a symptom of serious mental disorder"
     - ii. Imagery ... possibly the conversion of another type of tinnitus into a more pleasant musical sound
4. Pseudotinnitus ... not arising from within the individual
   - A. Environmental ... a real, low-level sound, or the sensation of sound arising from some electromagnetic emanation
   - B. Feigned ... the majority of cases arise in the medicolegal context, where the motive is financial gain

Uncertainties intrinsic to the field of tinnitus diagnosis call for a compromise approach, that of suggesting the most likely, reasonably probable diagnosis. "In fact, the diagnosis often has to be multiple, since most cases of tinnitus are associated with cochlear disorders and most of them have more than one cause."

SMITH and CANALIS (1989)

Five cases are discussed of otosyphilis in patients with Human Immuno-deficiency Virus infection. The group is representative of the known stages of the disease, from asymptomatic carrier to the fully expressed Acquired Immune Deficiency Syndrome.

In each case of syphilis affecting the cochlea, the audiogram showed a sensorineural loss. The losses were both unilateral and bilateral, with flat losses, and both high- and low-frequency sloping losses. In some cases, tinnitus was present. One patient exhibited a bilateral, symmetrical 4 kHz notch audiogram; no history of noise exposure was given.

GUPTA and VISHWAKARMA (1989)

A number of young people gave hearing thresholds before and soon after an Indian festival celebrated with the use of firecrackers. Children and young people, up to 31 years, were tested by manual audiometry at the frequencies 0.25 to 8 kHz. Six hundred participants were chosen from those who had no complaints of hearing loss, no history of ear infection or head injury, and who exhibited neither elevated threshold nor air-bone gap. Of this group, those who exhibited a loss immediately after the festival were examined after one month and again after three months.

Of those subjects whose hearing loss persisted for three months postexposure, that is, essentially permanent, the mean threshold shift at 4 kHz was 29 dB. At 6 kHz, the mean shift was 7 dB, giving the mean audiogram a sharp notch. These losses occurred in 2.5% of the six hundred participants; the authors attribute these hearing losses to the widespread use of fireworks.

LEVINE et al (1989)

The audiometric records of 161 patients with unilateral chronic otitis media were reviewed for indications of sensorineural hearing loss as a consequence of the middle ear infection. The diagnosis of otitis media was based upon a physical examination showing perforation of the tympanic membrane, cholesteatoma and/or ossicular destruction. A number of exclusions operated to ensure rejection of cases with hearing loss from extraneous causes. The subjects chosen were 79 males and 82 females; age ranged from 5 to 87 years. The normal ear of each subject served as the control for the diseased ear.

For each subject, bone-conduction thresholds for the normal ear were subtracted from those of the diseased ear. Mean b-c threshold differences for the subject sample are presented below, for each audiometric frequency.

frequency, kHz	0.25	0.5	1	2	3	4
difference, dB	5.6	9.3	6.5	12.8	11.4	9.1

The authors interpret these results as indicating inner ear damage as a sequel to chronic otitis media. No account is taken of the well-documented 'Carhart Effect', estimates of which are given in CARHART (1950), GUNDERSEN (1973) and GATEHOUSE and BROWNING (1982). When the authors' results are adjusted to account for inaccuracies of b-c threshold measurement in cases of conductive hearing loss, the differences between diseased and normal ears evaporate. The reviewer must disagree with the authors - there appears to be no inner ear damage as a sequel to chronic middle ear infection.

KURIEN et al (1989)

Hearing threshold levels were compared between a group of 30 diabetic patients and a group of 30 healthy controls, all under 50 years of age and without otological disease. The diabetics were separated into groups according to age, duration of disease, complications and control of the disease (as indicated by blood sugar measurements).

Comparing the mean thresholds for frequencies ranging from 0.25 to 8 kHz, the control group had the more acute thresholds. The diabetics were poorer by about 5 dB for the frequencies 2 kHz and below. For the frequencies 4, 6 and 8 kHz, the diabetics were approximately 20 dB worse. The effect of increasing age was also evidenced as increasing hearing threshold differences between the control and diabetic sub-groups, with significant differences at 6 and 8 kHz. Of the diabetics, those with neuropathy, retinopathy, nephropathy and/or vascular disease exhibited poorer high-frequency thresholds than did the uncomplicated cases. Poor control of the primary disease was also associated with poorer high-frequency thresholds.

These trends, although found to be statistically significant by the authors, should be held as preliminary. For several of the group comparisons, samples as small as seven subjects were used. Such small numbers do not inspire confidence in the study results; obviously more subjects are required if the total patient group is to be sub-divided to test sub-hypotheses.

PAPARELLA et al (1989)

The authors review the seemingly legion aetiologies of sensorineural hearing loss in children. Some losses are severe or profound, and may occur in combination with other crippling (and visible) abnormalities. These syndromes are not of primary importance here, as the sufferers would be plainly seen as not members of the normal population. In contrast, pre- or perinatal factors resulting in partial hearing loss are of interest here. A number of more or less common episodes or conditions have been associated with sub-total (possibly even subclinical) hearing damage. Among these are:

1. a family history of impaired hearing either from birth or developing in later life;
2. congenital or prenatal infections;
3. ototoxic drugs in either the pre- or post-natal period;
4. anoxia at birth; other birth trauma; and
5. birth weight less than 1500 grams.

Impairment to the hearing does not always result from the factors above, which leads one to suspect that a continuum of damage may exist. Some of the affected may be unnoticed in an unselected, seemingly normal population.

Conclusions on Otological Normality

From the reviews presented here, it may be seen that there exists a constellation of findings, feelings, history and hazards which signify some threat or risk to otological normality. Instead of the chronological ordering as seen above, a different grouping scheme will be pursued. Listed first, for convenience of thought, are findings and feelings related directly to the ear; listed second are episodes and risks from the past medical history; and last listed are activities known to carry some risk to the hearing organs or hearing function.

The first group of contra-indications is composed of signs and symptoms directly related to the ear and hearing function.

1. History of ear or mastoid surgery.
2. Observation or report of ear discharge (not wax).
3. Perforation or rupture of the eardrum.
4. Scarring observed in the eardrum.
5. Retraction of the eardrum.
6. Any sign of current infection of the canal, drum or middle ear.
7. History of persistent ear pain.
8. Fluctuating hearing loss.
9. Persistent tinnitus.
10. Unfavourable results for Rinne and/or Bing tuning fork tests.
11. Discovery of a foreign body in the external ear canal.
12. Otosclerosis

The second group of hearing risk factors may be found in the medical history. For convenience here, the factors are arranged in roughly chronological order, that is, as they might occur in infancy, childhood and then adulthood.

1. Genetic factors, manifested as deafness among blood relatives.
2. Maternal rubella, especially during the first or second trimesters of pregnancy.
3. Premature birth, with neonatal anoxia or very low birth weight.
4. Neonatal blood disorder, such as Rh-incompatibility.
5. Neonatal jaundice.
6. History of measles, mumps or bacterial meningitis.
7. Congenital or acquired syphilis.
8. Use of aminoglycoside antibiotics.
9. Use of diuretics.
10. Use of anti-malarial drugs.
11. Fractured skull, or any other head trauma resulting in loss of consciousness.
12. Otosclerosis.
13. Balance disorder.
14. Diabetes mellitus.
15. Renal disease.
16. Disorders of the circulation.
17. Toxaemia.

The last grouping of hearing risk factors is found in a person's activities, both recreational and occupational. The reader will notice that occupational noise exposure is not listed as a risk to otological normality, although known to be a cause of hearing damage. This exclusion is made to avoid the charge of a circular argument; it might be necessary to assess a person's claim to otologically normality in a case of noise-induced hearing loss. The following may be considered to be contra-indications.

1. Unprotected exposure to the sound of weapons fire in the military context.
2. Close proximity to fireworks or other explosions.
3. Noisy recreational activities, such as motor racing, sport shooting, DIY involving power tools, attendance at popular music events, etc.
4. Scuba/sport diving, or diving as an occupation.

5. Occupational or other repeated exposure to certain chemicals, among which are carbon tetrachloride, benzene, carbon disulphide, lead and arsenic.
6. Smoking.

With the factors set out in an ordered manner, it is easier to take stock, to make comparisons and see contrasts between the factors known or thought to be contra-indicative of otological normality. Certain factors have face validity; otosclerosis and middle ear infections are disease processes acting directly upon the ear to produce hearing impairment, while episodes of balance disorder indicate degeneration or disease of the labyrinth. Other systemic diseases produce hearing impairment only as a secondary manifestation; renal failure and disorders of blood circulation (perhaps aggravated by smoking) affect the hearing through the blood itself, or through embarrassment of the blood supply. Due to placement of the labyrinth within the temporal bone of the skull, the blood supply to the encased organs is by the single access route of the internal auditory meatus. Such a single spur to each ear, without collateral circulation, makes the inner ear (and the acoustic nerve which also passes through the internal auditory meatus) particularly vulnerable to disorders or interruption of the blood supply.

It may also be seen from the list above that certain factors may be well-known or easily verified, while others may be obscure (or obscured). Perforation of the eardrum is readily observed. Use of military firearms in National Service may be assumed for males over a certain age, and is a matter of record. In contrast however, an individual will almost certainly be unaware of his or her weight at birth, or the name of any drug, antibiotic or otherwise, used at some time in the past; an individual may not wish to admit of syphilis, congenital or acquired.

Several comments may be made to conclude the discussion of otological normality. Several of the hearing risk factors listed are known popularly to cause serious, even profound, hearing impairment. This is the end of a continuum, however; other degrees of less extreme hearing loss may exist. Maternal rubella provides an example.

German measles during the first trimester is known to be a strong teratogenic influence on the unborn child, producing characteristic multiple handicaps; during the second trimester of pregnancy, the teratogenic influence of maternal rubella is somewhat attenuated, being associated with lesser hearing losses with fewer individuals affected. Measles after birth still represents a risk to hearing, through viral infection of the inner ear, but only for a few individual sufferers. This one disease serves to illustrate the continuum of possible hearing loss, from subclinical to severe. At the low-loss end of this continuum, the hearing deficit may be so small as to be indistinguishable from the high hearing level tail of the normal distribution, that is to say that the tails of the pathological and normal distributions may overlap, making it difficult to place an individual in one population or the other. It is inevitable that some individuals are placed in the wrong population; the situation of interest here is the one obtaining when a person with undiscovered pathology is declared to be otologically normal, through insufficiently probing screening.

Lastly, it must be realized that otological normality, like the state of virginity, may be lost only once. A person may well be normal at some stage in his or her life, but once otological normality is lost through some pathology or hazardous activity, it may not be regained. This process implies that individuals are constantly being removed from the normal population, due to adventitious (but possibly minimal) hearing loss; the normal population is, however, constantly 'refreshed' as new, younger members take the places of those fallen from grace. A further implication emerges: the otologically normal population must be heavily weighted with younger individuals who have only a limited lifespan in the normal population. As time passes, so the opportunity accrues for adventitious pathology, with the result that the older otologically normal person becomes the exception, rather than the rule.

HEARING POPULATIONS : IDEAL AND REALISTIC

In the previous chapter, the distribution of hearing levels for the otologically normal population was shown to be unsymmetrical. For hearing levels elevated from the median, the distribution was wider, more disperse, than for hearing below the median. A simple hypothesis was put forward to explain the long tail into higher threshold values: a certain proportion of individuals, although apparently normal, are subject to hearing risk factors in the form of undiscovered ear pathology, systemic disease, or unrecognized hazardous activities. Such hearing risk factors will produce small amounts of adventitious hearing loss, so small as not to arouse suspicion that the affected individual is no longer normal, but now damaged. In the seemingly normal population, the effect of such obscure hearing losses will be to slightly inflate the population mean. Such an effect is recognized, and is counteracted by the use of the median as the statistic describing the central tendency of the population variable. However, small amounts of adventitious hearing loss may be seen in the population dispersion, as a skewed distribution.

If one accepts the idea that a seemingly otologically normal population contains individuals with obscure hearing risk factors, certain questions must be entertained. At what point does an individual (or sample) accumulate 'sufficient' hearing risk (or even hearing loss) to cease to be normal? As hearing risk accumulates with age, that is, with further time of opportunity for pathology etc. to accrue, how would hearing levels change with age and increasing hearing risk? At what level of accumulated risk (or age) do the majority of individuals lose their normality, and if most are no longer normal, is normality a fair standard?

The Otologically Typical Population

These questions about the fall from otological normality are best dealt with by consideration of a new class of survey population - typical. The otologically typical population would consist of individuals who may or may not have had episodes of ear disease, who may or may not be suffering from any number of systemic diseases known to affect hearing function, and who may or may not engage in hearing-hazardous activities. This new population of potential subjects could be called unscreened as well as typical. For our purposes, the specification of normal and now typical hearing, one exclusion recommends itself: the typical, unscreened population should not include individuals exposed to intense occupational noise. Noise-damaged hearing is not the typical or usual state of human health.

What follows are a few summaries of work specifying the hearing of the unscreened, typical population. The first is a report of a single hearing survey, included here as an example. The other summaries are themselves reviews of many such individual surveys, attempting to discern general trends from the works of many investiators. Adventitious hearing loss is admitted in the samples reviewed, to attain a representation of the general population as it would be found at any age.

The Reviews

BERGER et al (1977)

In an effort to provide a baseline against which to quantify industrial noise-induced hearing loss, hearing threshold levels were obtained from an unselected American sample covering a wide age range. Of the 334 males and 439 females taking part in the survey, the majority were visitors to an urban shopping district. This accounts for a sizable number of children in the sample, which covered the age range 5 to 79 years. Medical screening of the subjects was not undertaken; the only exclusion criterion was a lifetime industrial noise exposure in excess of two weeks. Non-industrial noise exposures, such as might result from military service, farming, hunting or hobbies, were considered normal to the population, and were not grounds for exclusion from the survey. All subjects gave thresholds by the self-recording method, after a minimal instruction period; it must be presumed that previous experience of audiometry was rare, even non-existent, among the subjects.

The overall conclusions confirm the results of previous research, namely:

1. hearing sensitivity deteriorates with increasing age;
2. loss of hearing acuity shows a frequency effect, with age losses for the higher frequencies being greater than those observed for the lower frequencies; and
3. the hearing sensitivity of men deteriorates faster than that of women.

In addition, the hearing of this unselected sample was found to deteriorate from a baseline displaced from audiometric zero. This trend is illustrated by the mean thresholds for 4 kHz, listed by age group and sex, for the unscreened group; these hearing levels are referenced to the audiometric zero specified in ANSI S3.6 - 1969 (which is identical to that of current British standards). For comparison, median thresholds are given for highly screened, otologically normal males and females; these values have been drawn from Shipton (1979).

HTL at 4 kHz, dB HL

age range, years	typical unscreened sample		age, years	otologically normal (highly screened) population	
	male	female		male	female
20-29	10	4	25	1	0
30-39	19	8	35	5	3
40-49	27	12	45	12	7
50-59	37	18	55	22	12
60-69	39	29	65	35	20

It will be seen that the typical males and females start from a higher hearing level and appear to deteriorate faster with age than do members of the otologically normal population. This is due to adventitious hearing loss accruing from episodes of ear disease and non-industrial noise exposure, common experiences for a typical population.

KRYTER (1983)

Before this paper appeared, there had been a significant number of studies and analyses of the hearing levels found in various general populations not exposed to high-level occupational noise. Some of these studies have been reviewed elsewhere in the present document; others have not been included here, as the American audiometric zero upon which the studies were based has been shown to be in error. Regardless, the author undertook to review more than 25 hearing surveys and to derive, as warranted, new generalizations with respect to the variables of age, sex, race, social/recreational noise exposure, and adventitious ear pathology.

From his critical analysis of the population hearing surveys, the author draws the conclusions listed below.

1. It appears that race and sex, on their own, are not significant factors in determining hearing thresholds.
2. Anomalies may be seen in the hearing pattern of any population. Certain sub-groups, even though screened to some degree, have hearing some 10-20 dB less acute than the randomly selected general population. These differences are suggested to be due to social/recreational noise exposure and adventitious pathology found in factory workers, but diluted in the general population.
3. The mathematical formulae derived by Robinson and Sutton (1978), and later incorporated in ISO 7029, do not represent the age effect on hearing in otologically normal persons as purported. Instead, the author is of the opinion that the formulae represent the effect of age, plus non-occupational noise exposure, plus adventitious ear pathology.
4. Females in industrial nations receive less noise exposure than do males, and also suffer less ear disease.
5. There is some evidence that ear disease in industrial nations is such as to increase the median hearing threshold, at all frequencies, by 1 to 2 dB for the general population and by about 6 dB for factory workers.

Several of these statements invite scepticism. It is not obvious why women should suffer less ear disease than men, or why workers should be particularly afflicted with ear disease. Careful reading of the contributions to ISO 7029 will reveal that, in most cases, subject screening was performed with some rigour to eliminate noise exposure and ear pathology. The author's denial of the documentary evidence seems perverse. Another perversity on the part of the author is the presentation in graphical form of his own representation of the relation between hearing and age with non-occupational noise and ear pathology. Mathematical formulation or tabular presentation of hearing levels would have been preferable. In graphical format, the author's conclusions are inaccessible to the serious student or reviewer.

ROBINSON (1988a)

A number of hearing surveys, each employing little or no selection of subjects for otological normality, have been critically reviewed, to form a typical population in contrast to the otologically normal population represented by ISO 7029. Contrary to the possibility that the typical unscreened population, which would include auditory deficits from the sub-clinical to the severe, might be rather indeterminate, a substantial consensus proved to be the case.

Hearing survey data, from 17 studies involving many thousands of subjects, were analysed to give statistics of age-related hearing loss for males and females of the general, unscreened population. Results of cubic regression analyses are given for frequencies over the range 0.5 to 6 kHz, for fractiles from the 5th to 90th percentiles, covering age from 20 to 70 years. Data have been extracted from the author's tables, for presentation here; the full tables are reproduced in the Appendix. Given below are hearing thresholds for males and females, covering the age range 20 to 70 years. To show the dispersion associated with each population, normal and typical, values are given for the 90th percentile (acute hearing), 50th percentile (median) and 10th percentile (dull hearing); thresholds are expressed relative to median hearing at 20 years for the otologically normal population of ISO 7029. These values are slightly higher than those given in ISO 1999, for a typical unscreened population of an industrialized country. The difference, which enlarges with increasing age, may be explained by the ISO choice of specifying HTL's for the better ear.

age years	4 kHz threshold, dB HL typical unscreened population 90%	50%	10%	otologically normal population 90%	50%	10%
males						
20	-4	4	27	-9	0	11
30	-2	10	45	-7	2	14
40	2	19	56	-4	8	23
50	7	30	64	0	16	36
60	14	43	71	7	28	55
70	24	56	81	15	43	79
females						
20	-5	1	12	-8	0	10
30	-4	4	16	-7	1	12
40	-3	7	24	-6	4	17
50	0	12	34	-3	9	24
60	4	19	48	1	16	35
70	9	31	65	5	24	48

The author offers the results of this critical analysis as a supplement to the otologically normal data of ISO 7029. The typical data, representing an unscreened population, would make a realistic baseline for the evaluation of hearing loss due to noise exposure in an industrial population.

INTERNATIONAL ORGANIZATION FOR STANDARDIZATION (1990)

This International Standard (ISO 1999) specifies a method for calculating the expected noise-induced threshold shift for adult populations exposed to various levels and durations of noise. The hearing threshold level of a particular noise-exposed sample is determined from the combination of a noise-induced threshold shift component, dependent upon the noise exposure parameters, and a hearing threshold level associated with the age of the study sample. This second component may be thought of as the hearing threshold level of non-noise-exposed population, of a certain age, to which is added a noise-induced loss.

For the age-loss only component, two data sets are offered. "Data Base A" summarizes the relation between age and hearing level for a highly-screened, otologically normal population; the hearing levels of this highly specialized population is standardized in ISO 7029. This otologically normal population is not necessarily best for all applications; another "Data Base B" is given, representing one specific unscreened, typical population. The Standard suggests that, if the amount of compensation is to be estimated for noise-damaged workers, and otological irregularities and non-occupational noise exposure are not or cannot be quantified in terms of hearing loss, then an unscreened population represented by "Data Base B" will be the more appropriate baseline for compensation.

Threshold data are given here for 4 kHz, for typical and otologically normal populations, that is, Data Bases B and A respectively. Values are given for males and females, at the ages of 30, 40, 50 and 60 years. Also given are thresholds for the 90th percentile (acute hearing), 50th percentile (median) and 10th percentile (dull hearing). The reader should note that the typical or unscreened population at each age shows a considerably wider range between the upper and lower deciles than is seen for the normals.

4 kHz threshold, dB HL

age years	typical unscreened population			otologically normal population		
	90%	50%	10%	90%	50%	10%
males						
30	-1	10	38	-7	2	14
40	4	17	50	-4	8	23
50	8	26	54	0	16	36
60	12	36	68	7	28	55
females						
30	-5	4	16	-7	1	12
40	-4	6	18	-6	4	17
50	-1	9	26	-3	9	24
60	4	17	43	1	16	35

These values for the typical, unscreened population illustrate the range of thresholds in the better ear, for adults in an industrialized country. The differences observed between the typical and normal populations may be attributed to adventitious ear pathology and social noise exposure which cause members of the normal population to drop into the typical group.

Conclusions on normal and typical populations

From the reviews seen here, one may conclude that the typical population exhibits hearing thresholds which are elevated in comparison to those of the normal population. The typical thresholds are also seen to be more widely dispersed, that is more variable, than for the normals. Both of these trends, higher and more widely dispersed thresholds for the typical population in comparison with the normal, are seen to become more extreme with increasing age, as may be seen in the values listed in the Appendix. This age dependence is the inescapable consequence of the accumulation of overt ear pathology and other hearing risk factors, all superimposed upon the hearing loss attributable to age alone.

The contrast between normal and typical populations has important implications for compensation in cases of noise damage to the hearing, even possibly in the identification of cases of noise damage. It must be repeated that, although otologically normal young people may be in the majority, with increasing age fewer and fewer members of the general population can claim to be otologically normal. In the higher age bands, normality must be considered rare. In any group of people, if otological irregularities and non-occupational noise exposure cannot be quantified in terms of hearing loss, then the typical hearing levels are recommended to characterize the hearing of the group. To make this contrast clearer, consider two groups of people, both determined to be otologically normal or very nearly so at the beginning of their collective working lifetime. One group works in a quiet environment; this quiet group exhibits decay of hearing sensitivity through the action of age, the expected but random episodes of ear disease and systemic disease, and the usual noise associated with living in a Western society. Through the action of all these typical pathogenic factors, our quiet group will exhibit a wide range of thresholds after an arbitrary period. In contrast, the other half of our hypothetical population works, without hearing protection, in a noise known to be hazardous to the hearing. This noise group is subject to the same pathogenic factors as the first quiet group, with the additional noise factor. At the end of the hypothetical working lifetime, the noise group will have hearing thresholds demonstrably elevated from those of the quiet group. Both groups are typical, indeed both groups may contain a few members who could claim to be otologically normal although identification of these individuals would be difficult. The damaging effect of the noise may be seen by comparing the thresholds of the noise group with its companion quiet group; the comparison is fair as the hearing of both groups has endured the same typical disease and social/recreational stresses. In this case the quiet, typical population is the control group against which to compare the noise test group. Otological normality does not come into the calculation of noise damage; the comparison is inequitable. Otological normality is the state of perfection, from which most members of our two groups have fallen, even without noxious noise acting on the hearing of one group.

PRESBYACUSIS

Introduction

Ageing of the whole body, and of specific organs, proceeds along an uneven front, occurring sooner in some cells and later in others. By the fourth decade of life, decreased efficiency may be observed in some organs, and in the individual as a whole. In the fifth decade, the reduction in efficiency becomes apparent. Further passage of time brings a cascade of senile changes, which usually end in death of the individual during the seventh or eighth decade.

The auditory system, like all systems of the body, exhibits senescent changes with the passage of time; these changes are manifested as age-related hearing loss, or presbyacusis. The degenerative changes, and the resulting hearing loss, have widely varying time of onset and rate of progression, determined as one might expect by genetic factors and the physical and chemical stresses imposed upon the hearing system during its lifetime. The age-related hearing loss is typically sensorineural in nature, affecting both ears equally, and is progressive. Usually, the higher frequencies are first affected, with the passage of time making the loss more severe, while widening the effect to include progressively lower frequencies. The course of threshold sensitivity decay may be predicted, in the population sense, with some confidence. Data exist which list, by age, the population fractiles expected to have a certain measured hearing loss at a particular frequency, for both males and females.

Not so predictable is the effect of age degeneration upon speech perception. In the case of presbyacusic hearing loss, speech comprehension and understanding shows a greater decrement than would be expected on the basis of pure-tone sensitivity loss exhibited on the audiogram. It is commonly held that the extra decrement is a slowing or loss of central processing, that is, beyond the cochlea in the higher auditory centres.

What follows are reviews pertaining to three aspects of presbyacusis : loss of threshold sensitivity; degradation of speech perception; and evidence and conclusions regarding histological changes in the cochlea. Concerning the loss of pure-tone sensitivity, the reader should be aware that this phenomenon does not suddenly appear in middle or later life; it starts quite early at the high frequency extremes of hearing, progressively narrowing the frequency limits of human hearing from a young age. By middle life, these senescent changes may be noticed as difficulty with speech perception under difficult listening conditions. These losses of detection sensitivity and processing power may be related in part to cell losses in the cochlea; as yet, age-related cell degeneration has not been documented for the central auditory pathways.

The Reviews

PESTALOZZA and SHORE (1955)

"The otologist who deals with elderly, hard-of-hearing patients knows how severe the hearing disability of his patients can be, even when the overall amount of hearing loss is not very great. He knows, furthermore, that two individuals with the same amount of hearing loss for pure tones can differ significantly in their perception for speech."

From this starting point, the authors undertook a series of studies of the auditory function of elderly, hard-of-hearing individuals. The overall aim was to determine if, by audiometric and psychoacoustic measurements, medical history, and clinical findings, it was possible to improve differential diagnosis of those hearing losses included under the generic term 'presbyacusis'. Of interest here is one study comparing the speech discrimination abilities of older and younger hearing-impaired subjects.

From the files of the Central Institute for the Deaf, in the USA, a number of presbyacusic cases were chosen for study on the following criteria:

1. age 60 years or older;
2. onset of hearing impairment gradual and progressive, over the preceding 10 years;

3. no findings of otological abnormality or previous ear disease; no history of serious illness; and
4. audiometric findings of symmetrical, sensorineural hearing loss, gradually worse with increasing frequency.

From the case records, and repeat tests, it was possible to establish a relation between average hearing threshold level for the three frequencies 0.5, 1 and 2 kHz (as the independent variable) and maximum discrimination score for phonetically-balanced words (as the dependent variable).

A younger group was selected to have hearing losses of the same type, and covering the same range of average HTL, as the older subjects. The younger group were all aged 40 years and under, with adult onset of hearing impairment (to be sure of normal development of language during childhood). For these younger subjects, maximum discrimination score was related to average HTL.

The discrimination-to-hearing-loss relations showed contrasts between the two subject groups, 40-and-under and 60-and-over. For the range of average HTL, 10 to 50 dB, the younger group had discrimination scores over the approximate range 80% and 50%. Over the same range of average threshold, the older group had discrimination scores covering the approximate range 70% to 25%. The authors concluded that poorer discrimination was associated with greater magnitudes of hearing loss, and that discrimination loss was definitely less in the group of younger individuals when compared to the older subjects with the same amount of hearing loss. In other words, presbyacusic hearing loss carries a speech discrimination decrement over and above that which might be predicted from the hearing loss alone.

HINCHCLIFFE (1959b)

A study was undertaken to determine how hearing threshold level changes with age for a random sample from the UK population. For each sex, fifty subjects were chosen in the age range 18 to 24 years, inclusive, to act as an auditory baseline group; 30 subjects of each gender were chosen in the age groups 25-34, 35-44, 45-54, 55-64 and 65-74 years. To be included in the analysis of age effects upon threshold, each ear was inspected and verified to be free of any signs of ear disease. Subjects were not excluded if noise exposure was reported. Hearing threshold levels were determined by manual audiometry at the frequencies 0.125, 0.25, 0.5, 1, 2, 3, 4, 6, 8 and 12 kHz.

At a few higher frequencies, 3, 4 and 6 kHz, male thresholds were found to be less acute than the females, even for the youngest age group, 18 to 24 years. The author attributed this gender difference to noise-induced threshold shift in the males, due specifically to firearms noise exposure. As the author had no reason to consider that there might be any basic difference in the ageing process affecting each sex, the median thresholds for the youngest female group were taken to be an arbitrary zero. As an illustration of the trends of the data, the median thresholds are given for 4 kHz, and for each age group.

median thresholds at 4 kHz, dB relative to youngest females

age group	female	male
18-24 yr	0	3.5
25-34	3.8	7.5
35-44	5.3	12.6
45-54	13.2	22.2
55-64	19.4	37.8
65-74	22.2	45.5

The author concluded that the course of the threshold of hearing for otologically normal females of various ages probably represented true presbyacusis. The median threshold of these female ears showed a deterioration at each audiometric frequency. Above 0.5 kHz, the rate of deterioration of threshold with age was found to increase with frequency.

GOETZINGER et al (1961)

A small survey was undertaken to document hearing function in advanced age. Ninety subjects were chosen in the age range 60 to 89 years, equally divided between males and females. Fifteen subjects of each sex were chosen for the age sub-groups 60 to 69, 70 to 79 and 80 to 89 years. The criteria for the inclusion of each subject were:

1. no history of hearing loss prior to age 50;
2. after age 50, hearing loss of gradual development and not associated with ear infection, accident, illness, drug therapy or noise exposure;
3. relative freedom from ear infections throughout life;
4. no history of occupational noise exposure;
5. little risk of noise injury from hunting or military service;
6. no indication that the subject suffered from senile dementia; and
7. the subject enjoyed relatively good health.

Air-conduction audiometry was performed using a manual, ascending technique for the octave frequencies from 0.25 to 8 kHz. Bone-conduction audiometry was performed for the frequencies 0.25 to 4 kHz. Mean air-conduction thresholds for each frequency are listed below for males and females within each age range. Responses could not be obtained at 8 kHz for all subjects, so no mean thresholds could be computed. Similarly, bone-conduction responses could not be obtained for all subjects; however, the responses which were obtained suggest that the hearing losses indicated below were all sensorineural in character.

frequency, kHz		0.25	0.5	1	2	4
mean HTL, dB HL						
	males					
age	60-69	7.5	10.2	10.8	21.0	42.5
	70-79	6.7	9.2	14.7	31.2	55.8
	80-89	16.8	18.5	26.8	43.8	64.0
	females					
age	60-69	11.8	10.2	10.3	18.7	27.8
	70-79	15.2	14.2	13.7	24.8	33.8
	80-89	23.8	22.7	24.7	32.5	49.3

It should be noted that the thresholds listed are referenced to the American audiometric zero current at the time the research was conducted; this standard is known to differ significantly from present American and International values for audiometric zero. The thresholds listed above indicate hearing which is erroneously acute; differences of thresholds within the table are, of course, valid regardless of the false zero.

Within the listed values, a number of trends may be discerned. Hearing levels become progressively elevated with increasing frequency, and with increasing age. Males suffer more high-frequency hearing loss with age than do females. In the lower frequencies the opposite trend seems to be operating; with females showing increasingly higher hearing levels than males in the same age band. The authors offer no hypothesis to account for the seemingly different processes of age-related hearing loss occurring in males and females.

NIXON et al (1962)

A comparison was made between bone-conduction threshold shifts and those for air conduction, as a function of age. For this study, 124 men acted as subjects; all were highly screened for otological normality. The men were divided into four subgroups, by age band : 35 men aged 20 to 29 years; 41 aged 30 to 39; 26 aged 40 to 49; and 22 in the range 50 to 59 years.

Each subject gave a-c thresholds for both ears, and a b-c threshold without masking, for the frequencies 0.5, 1, 2 and 4 kHz. For both a-c and b-c thresholds, data are reported as shifts relative to the youngest age group. As masking was not used during the b-c threshold determinations, the b-c values may be associated with the better ear a-c thresholds. The data show that the a-c thresholds increased, that is, became less acute, with age at a faster rate than did the b-c thresholds. This age-dependent air-bone gap was largest for 4 kHz; the effect may be seen in the values listed below.

mean threshold shift, dB

age group yr	better ear a-c	b-c
20 - 29	0	0
30 - 39	5.5	1.5
40 - 49	10	4
50 - 59	17	5

These data would appear to show an age-dependent, high-frequency conductive hearing loss among the subjects screened for otological normality. The authors attribute this loss to "a gradual diminishing of the mechanical integrity of the articulations or couplings of the ossicular chain. Consequently, vibratory energy is dissipated at these junctures." This hypothesis, if true, and if responsible for even greater air-bone gaps at 6 and 8 kHz, would weigh heavily against the widely accepted explanation of presbyacusis as a generalized deterioration of the cochlea and neural auditory pathways. The challenge has not been taken up by subsequent researchers; no further data have appeared documenting the age relation between air- and bone-conduction thresholds.

SPOOR (1967)

In an effort to account for the effect of age in the relation between noise exposure and noise-induced hearing loss, the author has critically analyzed the trends reported by eight researchers. The research reports analysed used the hearing thresholds levels for men and women of both highly screened and unselected samples. The result of the analysis was a single equation giving hearing threshold level as a function of age; appropriate constants allow the equation to be applied to males or females for any audiometric frequency from 0.25 to 8 kHz. Given here as sample results are the expected hearing threshold levels against age, for 4 kHz.

age yr	4 kHz threshold, dB HL male	female
25	6	3
35	12	6
45	19	11
55	29	17
65	40	26
75	54	37

These data show that even for the youngest age groups, males show worse hearing than do females; this disparity between genders grows more extreme with increasing age.

It is unclear in this article if the expected hearing levels are intended to be means or medians; the difference would be significant if the threshold distribution were skewed to any great degree. This uncertainty is resolved in a subsequent report, Spoor and Passchier-Vermeer (1969), which gives interquartile ranges about the median. The 1969 median hearing levels, for males and females of increasing age, agree with the expected values of this 1967 report, as given above.

BERGMAN (1971)

Many studies have reported that hearing threshold become less acute with advancing age. Older people also experience greater difficulty in understanding speech than would be expected from the pure-tone threshold levels. The author reports a study of speech performance, for various signal degradations and competing noises. The effect for the subjects, ranging in age from 20 to 89 years, was to markedly reduce the high redundancy of information, giving a performance degradation.

The subject pool comprised 352 adults; of these 282 passed a pure tone screening test (35 dB HL at 0.5, 1 and 2 kHz, 40 dB HL at 4 kHz) which the authors felt should have indicated normal hearing for average-level conversational speech. The subjects' performance showed little degradation with age, for undistorted speech without competing noise. For more difficult listening tasks, such as reverberated or time-interrupted speech, considerable decrements were observed. For some distorted speech tasks, scores were degraded by approximately 30% for subjects as young as 50 years.

The author comments that in persons of middle and later age, the understanding of speech under conditions of distortion, time alteration and competing signals shows marked deterioration, even when the hearing is relatively normal. It is suggested that the major age changes are related to a gradual decrease in the time-processing abilities.

JOHNSSON and HAWKINS (1972)

In order to establish the age-related degeneration pattern of sensory and neural structures in the inner ear, a number of temporal bones were studied by microdissection. These human tissue samples were obtained from 150 patients, ranging in age from foetuses and neonates to 97 years.

Hair cell degeneration was found in infants and neonates; this hair cell loss was observed as incomplete rows of outer hair cells at the extreme basal end of the cochlea, where extremely high frequencies would be transduced. By the early teens, missing cells were observed in the inner hair cell row at the extreme basal end; neural degeneration secondary to hair cell loss was clearly manifested.

In the cochleae of older patients, severe hair cell loss and nerve degeneration seldom extended above the lower half of the basal turn of the cochlea. This degeneration is consistent with the loss of hearing sensitivity from 2 or 3 kHz upwards, the pattern usually associated with presbyacusis. In the cochleae of patients exposed to excessive noise during life, a different degeneration pattern was observed. Most commonly, there was a localized, even sharply defined lesion in the middle of the basal turn, with hair cells and nerves surviving on both sides of the gap. Such a lesion is consistent with the 4 kHz notch usually observed in cases of noise-induced hearing loss.

These observations of cell loss with increasing age suggest that the process of presbyacusis starts almost from birth. Hearing sensitivity at the extreme high frequencies is the first to be dulled and then lost altogether. At such high frequencies, perhaps in excess of 20 kHz, hearing lost is perhaps not noticed. Only much later in life, in the 40's or 50's, does the loss start to intrude into the audiometric frequencies, 8 kHz and below, where it can be reliably measured.

SCHUKNECHT (1974)

In this textbook of ear pathology, the author presents, among any number of topics, a summary of his own research on the histological basis of presbyacusis; his work in this area has spanned a considerable period, see Schuknecht (1955, 1964 and 1967). The author identifies four types of presbyacusis, based upon the selective atrophy of different structures in the cochlea. These cellular structures may be involved singly or in combination. When the atrophy is confined to one structure alone, a characteristic pattern of hearing dysfunction will be exhibited, which may be identified by medical history, otological examination and hearing testing. A number of illustrative cases are presented; audiograms are shown against cell losses along the cochlear duct, observed post mortem.

1. Sensory presbyacusis is a well-documented disorder characterized by atrophy of the basal end of the Organ of Corti; it is manifested by abrupt high-frequency hearing loss. The degeneration, which results in hair cell loss, begins in middle age, and progresses bilaterally very slowly even in advanced age.

2. Neural presbyacusis is part of the generalized loss of nerve cells in the central nervous system, which is known to begin early in life and to continue until the death of the individual. Neural presbyacusis may begin at any age, but it seems to have little or no effect upon hearing until later in life, when the population of neurons falls below an apparent limit required for effective transmission, integration and decoding of the patterns

of neural signals. A loss of cochlear neurons creates a distinctive auditory dysfunction characterized by a loss of speech discrimination despite stable pure-tone thresholds.

3. Strial presbyacusis refers to atrophy of the stria vascularis, the organ within the scala media (with the hair cells and Organ of Corti) richly supplied with blood vessels. The clinical feature which distinguishes this form of presbyacusis is the flat audiometric pattern, usually associated with approximately normal speech discrimination.

4. The final form of age-related hearing loss, cochlear conductive presbyacusis, has not been demonstrated to be a pathological entity, although there is a presbyacusic pattern showing a bilateral, symmetrical gradually sloping audiogram with high frequency loss. Speech discrimination loss is directly related to the slope of the high frequency portion of the audiogram. Microscopic examination of affected cochleae, post mortem, has failed to reveal any morphological changes in the sensory or neuronal structures which would explain the observed hearing dysfunctions. The author speculates that the hearing loss is due to some disturbance of motion mechanics along the cochlear duct.

Although the histological causes of presbyacusis may be explained (or hypothesized), there are no therapeutic measures which alter the course of presbyacusis. Once the condition is established, it remains for the rest of the individual's life as a symmetrical, progressive hearing loss.

MILNE and LAUDER (1975)

This paper reports the hearing levels of older people, aged 62-90 years, drawn randomly from general practice lists in Edinburgh. The sample comprised 215 men and 272 women. No screening for noise exposure or otological normality was undertaken; the only exclusion (9 persons) was intellectual impairment, presumably senile dementia, of such a degree as to make audiometry impossible.

The hearing tests were performed using a single descending level series for the frequencies 0.25, 0.5, 1, 2, 4, 6 and 8 kHz. This method was chosen for speed of administration, rather than accuracy of threshold results.

The hearing of each age group was represented by the median threshold for the sample of better ears. Both sexes showed increases in hearing loss, for each frequency, with increasing age. Hearing threshold was greater in women for frequencies of 1 kHz or less and in men for frequencies of 2 kHz and above. This trend is illustrated by the median threshold levels given in the table below.

	median thresholds, dB HL			
age group	0.5 Hz		4 kHz	
yr	male	female	male	female
62 - 64	17	25	39	22
65 - 69	23	30	45	30
70 - 74	30	30	60	34
75 - 79	25	34	52	51
80 -	28	41	83	56

No explanation is offered for the worse low-frequency hearing in women. For the men, poorer high frequency hearing is attributed to occupational noise exposure. Although not mentioned by the authors, military service in the Great War might well be seen in the hearing levels of males aged 70 years and over.

The audiometric method employed for this study has little to recommend it save speed of administration. Although comparisons within the results of this study may be valid, comparison with other studies is not advised.

BERGMAN et al (1976)

Two hundred and eighty-two adults took part in an American study of ageing and hearing for speech. The subjects, whose first language was English, were drawn from a variety of work and home settings, and from different socio-economic groups. The age distribution is given in the table:

age range, yr	subject numbers
20 - 29	36
30 - 39	48
40 - 49	50
50 - 59	41
60 - 69	41
70 - 79	48
80 - 89	18

These subjects all had hearing thresholds better than 35 dB HL (ISO) at 0.5, 1 and 2 kHz, and 40 dB HL at 4 kHz.

Sentence intelligibility tests were performed under a number of conditions listed below.

1. As a reference of control conditions, sentences were presented in quiet, and free of distortion.
2. Similar sentence lists were presented interrupted or chopped 8 times per second.
3. Some sentences were presented at a rate of 300 words per minute, i.e. 2½ times the normal speed of 120 words per minute.
4. Some were split into high- and low-frequency bands for presentation to opposite ears, so that the full frequency content had to be 'assembled' in the central auditory system.
5. Another test presented sentences against a background of competing voices.
6. To simulate unfavourable listening acoustics, sentences were presented with "less-than-favourable" reverberation.
7. In the only test of words in isolation, different two-syllable words were presented to the opposite ears in such a way that the final syllable of the first word overlapped in time the initial syllable of the second word.

As may be concluded from the conditions tested, the authors were seeking a relation between age and central auditory ability. Results were presented as percentage score decrement against age, for undistorted and distorted speech. In relation to the scores for the youngest subjects, 20-29 years, the undistorted speech intelligibility remained relatively unaffected until age 80-89 years. For the distorted speech, large score decrements were in evidence for subjects as young as 40-49 years. All forms of distorted speech showed an intelligibility decrement by the age 60-69 years. The authors generalize their findings to conclude that for less-than-perfect listening conditions, the perception of everyday speech declines significantly with increasing age. This natural change is noted as early as the 40's, with a sharp acceleration occurring in the 60's.

JERGER and HAYES (1977)

The authors report the results of a series of experiments using combinations of speech tests, in a programme to produce more useful diagnostic information. The speech material was of two contrasting qualities. Phonetically-balanced monosyllables were thought to be particularly useful in cases of peripheral, cochlear hearing loss; word discrimination scores may be relatively well predicted if the shape of the audiogram is known, in cases of cochlear sensitivity loss. Synthetic sentence identification against a background of continuous speech discourse was chosen as a very much more difficult task than single words. The sentence task was particularly susceptible to central auditory disorder, even to the level of showing, by sentence identification score disparities between ears, which side of the brain is affected. For both word and sentence tests, performance curves were determined which related the score on each test to the signal presentation levels. The authors found, over many audiological investigations, that certain relations between the performance curves for the word and sentence tests provided information for differential diagnosis of the site of lesion.

The authors considered the effect of age on speech test results to indicate a special case of central auditory involvement. To illustrate the effect of age, the authors gave word and sentence scores for a series of 204 patients with screened sensorineural hearing losses. The test results were given by age decade for the subjects from 10 to 90 years. The single-word test results were relatively stable at levels commensurate with the cochlear hearing losses; only a gradual age effect could be seen, with the word scores declining from about 80% to 70% over the complete age range of the subjects. For the sentences-in-noise tests, an age effect was plainly exhibited. The sentence scores declined slightly from youth to about age 45 or 55 years. From this age band, sentence-in-noise test results declined at a much faster rate. The authors interpreted these results as indicative of the increasing proportion of central auditory involvement to the hearing loss associated with advancing years. A hypothesis was advanced: speech test results may yield a rough estimate of the relative contributions of cochlear and central effects to the total auditory dysfunction of individual patients. This factor, the "peripheral-central ratio" may ultimately prove useful in judging the prognosis for successful use of a hearing aid or other rehabilitative measure.

ROBINSON and SUTTON (1978)

As a contribution to the standardization of normative audiometric data, the literature on presbyacusis was critically reviewed. Data from the literature, in the form of pure-tone hearing threshold levels, was subjected to critical numerical evaluation. A formula was derived for generating the age effect upon hearing threshold levels for the frequencies from 0.125 to 12 kHz inclusive, for groups of otologically normal males and females.

The formula resulting from the synthesis of a number of data ensembles may be used to calculate threshold shifts relative to the hearing threshold level at age 18 years. Given below are values of median threshold shift at 4 kHz, relative to the reference age, for males and females.

age	4 kHz threshold shift, dB	
yr	males	females
18	0	0
25	1	0
35	5	3
45	12	7
55	22	12
65	35	20

These data show that hearing sensitivity for otologically normal males deteriorates at a faster rate than for females. Absolute comparisons between genders may not be made using these values; audiometric zero values are not given for youngest otologically normal males and females, but they are known to be equal within a decibel or so.

Following on from this critical numerical analysis of the presbyacusis literature, the authors' formulae and coefficients were used to produce tables of pure-tone thresholds against age. These tables, see Shipton (1979), give values of age correction for males and females in one year steps from 20 to 70 years of age, for the population fractiles 0.01 to 0.99, for the audiometric frequencies 0.125 to 8 kHz. The Robinson and Sutton formulation also forms the basis of International and British Standards, ISO 7029-1984 and BS 6951:1988 respectively, specifying the threshold of hearing by air conduction, as a function of age and sex for otologically normal persons.

HUIZING and HOOGENDIJK (1980)

The audiometric data have been analyzed from a consecutive series of 200 patients (400 ears) diagnosed as suffering from presbyacusis. The results may be summarized as below.

1. A sloping, high frequency audiometric form is the most frequent (85%) type of presbyacusis. However, flat audiograms were found in 13% of the cases, with ascending curves (low-frequency thresholds worst) found in 2%.
2. Maximum slope of the audiogram was found to be about 10 dB per octave.
3. The average speech discrimination in patients with flat audiograms did not differ from that of patients with the high-frequency, sloping audiograms.

The authors state that these findings do not support the long-standing hypothesis that presbyacusis is the manifestation of four separate disorders of the cochlea and its peripheral nerves, expressed singly or in combination; see SCHUKNECHT (1974). This conclusion is not elaborated in the brief report. It is clear, however, that apart from the classical high-frequency, sloping form of presbyacusis, a flat loss is a relatively frequent manifestation of age-related hearing loss.

HAYES (1985)

The author draws together research conclusions from many quarters, and presents a cogent summary of presbyacusis, the most common cause of hearing loss in adults.

> "As a clinical entity, presbyacusis has two distinct components. The first is related to changes in the auditory periphery, primarily the cochlea. The peripheral component of presbyacusis is manifested mainly by changes in pure-tone sensitivity. The second component of presbyacusis is related to changes in the central auditory system. This component is manifested by **loss in the ability to understand speech, especially in difficult listening conditions.** The interaction of these two components, peripheral and central, makes presbyacusis an exceedingly complex clinical problem."
>
> (Emphasis by the present reviewer.)

The burden of the author's message is that age-related changes in the cochlea depress the hearing thresholds, frequently giving a gradually sloping, bilaterally symmetrical audiogram. Such a high-frequency hearing loss results in an initial distortion of any sound entering the auditory system. The threshold distortion influences the audibility of certain speech sounds, giving broadly predictable changes in discrimination. The unique feature of presbyacusis is that the degraded speech signal, coded for transmission to higher auditory centres, must be decoded by a central nervous system that has also been affected by age-related changes.

The two components of age-related hearing loss, peripheral and central, may occur singly or in combination. In any individual, the interaction of peripheral and central components may be assessed by consideration of the hearing threshold levels, and speech audiometry with tasks of varying difficulty. Speech tests employing single words are considered relatively easy, and primarily sensitive to cochlear deficits. In contrast, sentence tests are relatively more difficult, showing up central auditory dysfunction. Easy and difficult speech audiometry tasks, used in combination, will reveal the wide range of peripheral and central effects, found in some degree in most elderly persons.

DRESCHLER et al (1985)

This paper reports a study of the use of high-frequency audiometry for the early detection of ototoxicity. In order to provide a baseline against which to test the hearing of patients receiving a platinum derivative, high-frequency thresholds were determined for 108 otologically normal ears, of male and female subjects covering the age range up to 70 years.

Using a conventional audiometer, the normal subjects gave thresholds for the frequencies 0.25 to 8 kHz. For the higher frequencies, from 8 to 20 kHz in intervals of 2 kHz, a special-purpose audiometer was used, with non-standard earphones. A sample of the results is given here, in the form of threshold shift relative to the hearing of the 20-30 year old subjects, for the frequencies 8, 12 and 16 kHz.

high-frequency threshold shift, dB

frequency, kHz	8	12	16
age range, yr			
20 - 30	0	0	0
30 - 40	7	21	27
40 - 50	7	37	47
50 - 60	29	66	-
60 - 70	38	77	-

These sample results show that hearing deteriorates more quickly for the higher frequencies.

SOUCEK et al (1986)

An investigation was undertaken in a hospital geriatric unit to determine the site of damage in cases of presbyacusis. Pure-tone audiometry was used to test the hearing of 159 patients (318 ears). Of these, brainstem evoked responses were obtained from 49 patients (80 ears); the responses were normal indicating no pathology in the brainstem. Extratympanic electrocochleography performed on 17 patients (21 cochleae) gave satisfactory potentials from the auditory nerve. This series of test results suggested a cochlear lesion at a level peripheral to the auditory nerve.

Temporal bone samples were obtained after death from 17 of the patients (25 cochleae). Histological examination of the cochleae showed severe loss of outer hair cells; alterations of the hairs were observed in the surviving cells. On the basis of these audiometric and histopathological findings, the authors suggest that degeneration of hair cells is the primary lesion of presbyacusis.

GREEN et al (1987)

The hearing thresholds of 37 young adults were determined at the frequencies 8, 9, 10 ... 19 and 20 kHz, using a newly developed high-frequency audiometer. The pure-tone signals were not presented by conventional earphones, but rather through a tube affixed in the ear canal by an earpiece. In this manner, the ear canal was simply an extension of the sound transmission tube. The instrument was so designed and operated that its acoustic output was specified in terms of SPL occurring at the end of the transmission tube, that is, at the eardrum. This novel feature of the instrument obviates the need of conventional calibration, and serves to 'calibrate' the acoustic output to each individual ear under test.

Thirty-seven subjects, between the ages of 18 and 26 years, participated in the survey. All subjects were screened to have hearing threshold levels less than or equal to 15 dB HL, for the conventional audiometric frequencies at octave intervals between 0.25 and 8 kHz. In addition, each subject was screened tympanometrically to ensure middle ear function within normal limits. One ear of each subject was tested to determine the threshold SPL at the 13 frequencies 8, 9, 10, ... 19 and 20 kHz.

The average threshold SPL at the eardrum was found to increase gradually with frequency, indicating lower sensitivity at the higher frequencies. There was no difference between males and females for any frequency. Grouping of the subjects into three different age bands revealed a reliable trend between threshold, frequency and age, as may be seen in the values below:

frequency, kHz	12	14	16	20
threshold SPL, dB				
age, yr				
18-20	27	32	52	76
21-23	30	38	60	88
24-26	35	49	76	104

These values indicate that sensitivity to high-frequency tones is decaying, or leaking away, early in life. It would appear that the high-frequency loss of hearing, usually associated with atrophy of the Organ of Corti in the basal end of the cochlea, begins quite early in life.

KEAY and MURRAY (1988)

This paper presents the results of a hearing survey in elderly people, with an interval of 17 years between first and last determination of pure-tone thresholds. Initially, 748 people were selected at random from the electoral roll; the fraction who agreed to participate in the hearing survey had an average age of 65 years. Five years later, 135 of the original participants again gave pure-tone thresholds by manual audiometry. Of this re-test group, 37 were able to give further thresholds at a second re-test, at an average age of 82 years, 17 years after first entering the study.

The results of the survey are listed as median hearing thresholds for the subjects at the first determination, average age 65, and the last re-test, at age 82 years.

median thresholds, dB HL							
frequency, kHz	0.25	0.5	1	2	4	6	8
average age 65	30	30	25	20	30	40	45
average age 82	35	30	35	40	50	70	85

The results indicate higher rates of loss in the higher frequencies, confirming that hearing loss continues steadily into the ninth decade of life.

ROBINSON (1988a)

A number of hearing surveys, each involving little or no selection for otological normality, were critically reviewed with a view to specifying HTL's by age and sex for a typical population, in contrast to the highly screened population represented in ISO 7029. Contrary to the possibility that the typical unscreened population might be rather indeterminate, due to inclusion of auditory deficits of degree ranging from sub-clinical to severe, a substantial concensus proved to be the case.

Hearing survey data, from many thousands of subjects, were analysed to give age-related hearing loss for males and females of the general, unscreened population. Results of regression analyses are given for audiometric frequencies over the range 0.5 to 6 kHz, covering age from 20 to 70 years. Data have been extracted from the author's tables for presentation here. Given below are the 4 kHz hearing thresholds for median males and females of the typical population; for comparison, the corresponding values are listed for the otologically normal population of ISO 7029.

median threshold at 4 kHz,
dB relative to young otologically normal hearing

age, yr	typical population male	typical population female	otologically normal population male	otologically normal population female
20	4	1	0	0
30	10	4	2	1
40	19	7	8	4
50	30	12	16	9
60	43	19	28	16
70	56	31	43	24

The author offers the results of this critical analysis as a useful supplement to the data of ISO 7029. The typical population, subject to adventitious hearing loss from any number of sources, would make a realistic and equitable baseline for the evaluation of hearing deficits due to noise exposure in an industrial population.

Note: Hearing threshold values, listed by age, sex and frequency, are presented in the Appendix for both normal and typical populations.

WRIGHT et al (1988)

Human temporal bones were examined for age-related changes in the number and distribution of cochlear hair cells. The cochleae studied were from individuals who had clinically normal hearing prior to death. Exposure to industrial noise or ototoxic drugs excluded a subject/sample from the study.

Fifty-six cochleae were dissected; counts were made of the inner and outer hair cells. There was a generalized loss of outer hair cells early in life; this loss did not correlate well with the audiometric pattern. However, the loss of inner hair cells, initially only slight, increased rapidly after age 50 years, correlating well with the pure-tone threshold data. The inference is that presbyacusic hearing loss is a function of loss of inner hair cells.

RAMADAN and SCHUKNECHT (1989)

A quantitative histological study was made of temporal bones from human subjects who, when alive, exhibited presbyacusic hearing loss without other otological disease. Temporal bones, containing the cochlea and eighth cranial nerve, were chosen if the patient had exhibited a high-frequency hearing loss, with a threshold difference of at least 60 dB between the most sensitive and least sensitive frequency. For the fourteen post-mortem samples selected, the age at death ranged from 53 to 90 years, with the definitive audiometric test performed no more than 8 years before death.

The temporal bones were divided into two groups, depending upon the slope of the associated audiogram. A gradual-slope group showed octave threshold differences of 25 dB or less. Threshold differences in excess of 35 dB over one octave placed a tissue sample in the abrupt-slope group. Each group comprised seven temporal bones. Hair cell counts were made by light microscopy; assessments were also made of the anatomical integrity of the constituent structures of the Organ of Corti.

The gradual-slope specimens showed small patches of hair cell loss, not correlating spatially with the audiometric pattern. On the other hand, the abrupt-loss specimens showed significant hair cell losses in the basal end of the cochlea, reflecting the audiometric configuration more accurately. Within each group, complex interactions were observed between the hair cell losses, and atrophy of the cochlear neurons and of the stria vascularis.

The investigators were unable to detect any histopathology clearly associated with the gradual-slope audiometric configuration. They speculate that the cause must be sub-cellular, acting upon a structure which associates or codes place of vibration as pitch of the sound causing the cochlear vibration. The basilar membrane is such a structure. The authors imagine that age might affect the vibration transmission properties of the basilar membrane. This is, as the authors admit, purest speculation.

The authors use the term "conductive presbyacusis". The word conductive usually refers to the middle ear; the application of the word to the inner ear is unhelpful. In any case, this form of presbyacusis has been discussed earlier, see SCHUKNECHT (1974). At that time, no structural changes were observed in the affected cochleae which might have accounted for the observed hearing dysfunction. Fifteen years later, there was still no histopathological evidence to explain the dysfunction. Perhaps the fault lies with the hypothesis of a disturbance of motion mechanics along the cochlear duct.

Conclusions on presbyacusis

Of the three aspects of presbyacusis, it appears that the loss of threshold sensitivity has been most thoroughly documented. Starting from a surprisingly early age, as early as the 20's, high-frequency threshold sensitivity begins to decay. This natural change is not noticed until perhaps two decades later, when the loss of sensitivity intrudes into the audiometric frequencies. With further increments of age, the loss of sensitivity continues to progress to lower and lower frequencies, intruding into the speech frequencies (below 3 or 4 kHz). The later phase is not marked in some striking or obvious fashion, but rather comes on by insignificant degrees.

As a consequence of the loss of threshold sensitivity, the perception of speech is affected. During the early stage of sensitivity decay, usually not thought of as presbyacusis as it occurs during the third to fifth decades of life, speech discrimination may be reasonably well predicted from the hearing threshold levels. However, the natural progression of presbyacusis will engage the central auditory processes at some time, usually during the 50's or 60's. Although the age of onset is not predictable, nor is the rate of deterioration, the central effects are first manifested as difficulty with speech in noise, particularly in social settings where the noise is voice babble. This loss or slowing of central processing is independent of, but superimposed upon, any cochlear (peripheral) hearing loss. It might be said that in cases of mild hearing deficit, the sufferer may well accommodate to the hearing loss until middle life; at this time, the central involvement of age-related hearing changes then intrude into the sufferer's consciousness, interfering with social discourse. The long-standing hearing deficit will be perceived (wrongly) as at fault for the new hearing difficulties, which are the natural process of senescent change.

The varied manifestations of presbyacusis have been examined from the cellular standpoint. Both sensitivity decay and loss of central processing are attributed to cell loss within the cochlea. Loss of threshold sensitivity is correlated with loss of hair cells, particularly inner hair cells, at the basal or high-frequency end of the cochlea. Dysfunction of the stria vascularis produces an effect upon hair cell metabolism, producing a sensitivity loss widespread over the frequency range. Neural involvement may be seen as cell loss in the cochlear neurons and in the lower stages of the eighth cranial nerve. Higher-level neural involvement must be inferred.

It must be repeated that these senescent changes are a natural and inevitable consequence of growing old. The age of onset and rate of onset of hearing difficulties will vary between individuals, as will the type and effect of the loss. Most people are not concerned with pure tones, high frequency or otherwise; it is the speech discrimination difficulties which are noticed, and which cause complaint.

Obscure Auditory Dysfunction

A topic closely related to presbyacusis is the recently-named Obscure Auditory Dysfunction, or OAD. This is the term applied to patients, usually relatively young, who complain of difficulty understanding speech, in spite of hearing threshold levels considered to be well within the range of normal. Very little literature exists on this topic.

The reviews

ALVORD (1983)

The author addresses the question: Can cochlear dysfunction be demonstrated in patients who, despite significant noise exposure, have normal hearing for pure tones? Such patients present with complaints of decreased ability to hear speech in noise. Ten such patients, attending a US military hospital, were chosen for comparison with ten subjects not exposed to noise.

The ten experimental subjects gave thresholds less than or equal to 20 dB HL for the audiometric frequencies 0.25 to 4 kHz, and 30 dB HL or less at 8 kHz. These subjects were all male, with age ranging from 23 to 57 years; all were noise-exposed. Control subjects comprised 3 females and 7 males, aged 30 to 58 years; all denied any history of noise exposure. The experimental measure was speech discrimination score, using a word list comprising monosyllables heavily loaded with high-frequency consonants such as voiceless fricatives and voiceless plosives. The word lists were mixed with speech-shaped noise at a signal-to-noise ratio 10 dB, and presented monaurally by earphone at a normal level. The test comparisons are set out below.

	mean threshold level, dB HL						discrim
frequency, kHz	0.25	0.5	1	2	4	8	score
exposed group	14.0	11.5	9.5	11.5	17.0	19.0	70.6%
control group	8.5	6.5	3.5	4.0	7.5	13.0	80.2%

The author found the speech discrimination in noise to be significantly higher for the control subjects. Although statistically significant, the discrimination difference between groups is unimpressive. The difference in sensitized speech test results may well be due to confounding of variables, and indicative of the difference in threshold levels between the exposed and control groups. In any case, the number of test subjects, ten in each group, suggests a minimal credible effort. The author's conclusion, that cochlear dysfunction has been demonstrated, must be viewed with circumspection.

RENDELL and STEPHENS (1988)

A small proportion of patients experience hearing difficulties despite apparently normal test results at the cochlear and retro-cochlear levels. The authors hypothesized six possible diagnoses for such hearing difficulties, and devised a test battery to test each diagnosis.

Subclinical cochlear damage was detected by sensitized measures of cochlear function, such as the gap detection test of temporal resolution, and high-frequency audiometry. Central dysfunction was tested using a number of measures, among which were dichotic listening and sentences in noise. Other possible diagnoses, less closely tied to auditory function, were impaired lip-reading and audio-visual skills, acoustically difficult work environment, and the use of English as a second language. Emotional and psychological difficulties were also considered as a final possible diagnosis.

At the time of their report, the authors had seen 26 individuals, of whom 19 were female. The ages ranged from below 20 years to 49 years. The individuals were apportioned between diagnosis categories: psychological; cochlear; work; language; and central. In some cases, multiple diagnoses were appropriate, as seen in the matrix below.

Numbers in each single or multiple diagnosis category

	Psych.	Coch.	Work	Lang.
Psych.	5			
Coch.	4	2		
Work	3	3	4	
Lang.	1			1
Cent.	1	1		

It will be noted that, in this patient sample at least, only 2 of 29 had hearing difficulties attributable solely to subclinical cochlear damage, presumably showing hearing threshold levels within (unstated) normal limits. The overwhelming majority of diagnoses invoke non-auditory components of hearing difficulty.

SWAN and GATEHOUSE (1989)

The authors report the investigation of twenty-two patients judged to be suffering from obscure auditory dysfunction, that is, hearing disability despite apparently normal hearing thresholds. A test battery was administered to the patients, on the assumption that concentration on central auditory function would shed light on the location of the dysfunction. The test battery employed staggered spondaic words, gap detection, binaural masking level difference and binaural speech-in-noise tests, among others. The results suggested to the authors that the OAD syndrome is, at least in part, a dysfunction of central auditory function, the auditory processing which occurs at levels beyond that of the cochlea.

SAUNDERS and HAGGARD (1989)

Most audiologists and otologists acknowledge the existence of a category of patients with normal audiograms, who complain of significant difficulty in discriminating speech in noise, particularly if the competing noise is also speech. The authors estimate that, in the UK, approximately 5% of adult referrals to ENT clinics are patients in this category. For the purposes of the research outlined here, such OAD patients are defined by the authors as having self-reported hearing difficulties, but no measured impairment exceeding conventional clinical criteria of normality, and no other obvious causes. A fairly strict definition of normal hearing thresholds has been adopted, being all thresholds less than or equal to 20 dB HL for each frequency up to and including 4 kHz, for both ears.

One aim of the study was to determine the basis of the OAD syndrome, and to provide a replicable clinical description of the syndrome. Twenty OAD patients were chosen, aged between 16 and 55 years; the upper limit was set to avoid degenerative, neural or cardiovascular pathology. For each OAD patient, two control subjects were recruited, to be matched for age, sex, socioeconomic status and noise exposure. Both OAD patients and controls were given a battery of tests, consisting of:

1. history taking;
2. a questionnaire on hearing disability/handicap;
3. pure-tone audiometry;
4. tympanometry;
5. determination of psychophysical tuning curves;
6. estimation of noise exposure;
7. sentence discrimination in noise;
8. a lipreading test;
9. a pencil-and-paper linguistic ability test; and
10. a psychoneurotic personality scaling test.

By definition and by selection, the OAD patients had hearing thresholds within normal limits. In comparison with the normal controls, the OAD patients had slightly less acute thresholds at all frequencies. For tympanometry and determination of tuning curves, nothing abnormal was demonstrated. In both the discrimination and lipreading tests, the performance of the OAD patients was reduced in comparison with the normal controls; linguistic ability was also reduced in the OAD group. Anxiety and history of otological disorder were found to be higher in the OAD group; the authors suggest that anxiety acts to enhance a patient's awareness of his or her hearing difficulty.

Within the OAD group, there was a large degree of variation in both measured performance ability and reported disability. The authors interpret this variation as indicating varying degrees of severity of OAD. An alternative interpretation is possible. As the syndrome seems to be defined by reported hearing handicap without significant measurable hearing loss, and anxiety and reduced linguistic ability seem to play a part, one might justifiably wonder if OAD is not an auditory dysfunction at all, but perhaps a personality disorder.

Conclusions on OAD

From the reports seen above, it is not clear whether obscure auditory dysfunction is a single condition or a collection of conditions affecting auditory function. It might just as easily be argued that OAD is not an auditory condition at all, as there appear to be a considerable number of extra-auditory factors at play. A watching brief is indicated.

One thing is clear, however: there exist a number of persons who complain of speech hearing problems which seem not to have a basis in elevated hearing thresholds. These 'OAD sufferers' might be thought of as early presbyacusics, but without the customary age and age-related threshold elevation. Just as presbyacusic hearing loss may focus the attention of noise-exposed persons, causing them to attribute rightly or wrongly their speech discrimination difficulties to a working lifetime in noise, so might OAD act in the younger person. It must be kept in mind, however, that OAD and presbyacusis also affect individuals who have no noise exposure; indeed, the two conditions are defined without recourse to any hearing risk factor.

THE LIMITS OF NORMAL HEARING AND THE ONSET OF HEARING DISABILITY

Bearing in mind the conclusions of previous chapters, it is now possible to deal with the problem of the limit of normal hearing and the level of onset of hearing disability or handicap. For this discussion, the term 'normal hearing' encompasses that of both the highly screened (otologically perfect) and the typical, unscreened populations. Alternative terms might be 'usual' or 'expected' hearing; these terms, however, do not convey quite the same sense as does the over-worked 'normal'.

The Range of Normal Hearing

One method of defining the limits of normal hearing is to start at the median, and move toward the dull-hearing tail of the distribution. For purposes of this discussion, the acute tail of the distribution is of little interest, as the objective is to define some threshold fence which separates normal hearing from suspected pathological or damaged hearing. From the median, elevation of the hearing level may be associated with various fractiles of the population. If the lower decile of hearing thresholds is chosen, quite arbitrarily, to be the fence dividing normal from suspect hearing, the implication is that 10% of the subject population has hearing worse than the associated HTL, and the remaining 90% has better hearing. It must be stated that this choice of the lower decile is made in an arbitrary fashion. The decile is, however, quite a generous or lenient choice; usual practice in statistics would require that the 5% or even 1% fractile of HTL be breeched before the particular case under consideration be deemed non-normal or damaged. Thus, choice of the decile as the fence value allows more individuals with suspect hearing to claim for themselves the title 'damaged', 'disabled', 'handicapped', or indeed whatever word is chosen to describe the territory on the far side of the lower decile fence.

Having arbitrarily selected the lower decile of HTL as separating normal from possibly non-normal, all that remains is to list the values. The reader will be aware that a number of values are possible.

Different thresholds would apply if the subject population comprises otologically normal individuals, or typicals. Males have been shown to have worse hearing than females. Age will most certainly be a factor. Fortunately, threshold values exist which account for all of these factors, even at the lower decile; these values are listed in the following tables. The thresholds for the otologically normal population are drawn from the tables of Shipton (1979), which lists values identical to those of ISO 7029. The typical thresholds are the result of the synthesis of unscreened populations, to be found in ROBINSON (1988a).

Referring first to the highly screened, otologically normal population, it may be seen that at age 20 the hearing of both males and females shows a small but positive deviation from zero. The observed effect is slightly more pronounced at the higher frequencies. With increasing age, the HTL's become more elevated from median young normal. At the highest age listed, 70 years, the thresholds show large elevations, especially in the higher frequencies, for those rare older individuals who show no signs of ear disease, and who have not suffered undue noise exposure, certainly not to occupational noise. For the typical population, the same trends may be observed even more clearly. The elevated thresholds start from a slightly higher level and deteriorate at a faster rate, all due to the ear pathology, systemic disease and social/recreational noise exposure which accumulates in a typical population.

The lower decile fence, arbitrarily separating normal from suspect hearing, has two obvious applications. For an individual without serious ear disease, general disease or hazardous noise exposure, but whose hearing levels fall on the unfavourable side of the fence, there may be some covert disease or unrecognized risk factor. Such a person has HTL's so elevated as to reject the possibility of that individual having normal hearing. In contrast to this situation is the person who is known to have suffered disease, otitis media for instance, or some other risk factor such as exposure to very loud occupational noise over a number of years, accumulating a total noise dose which would produce a reliably measured hearing loss

Lower decile of an otologically normal population "without undue exposure to noise", thresholds in dB relative to median threshold at 20 years

frequency, kHz	0.5	1	2	3	4	6
age, years						
males						
20	8	8	9	10	11	12
30	9	9	11	13	14	16
40	11	11	15	19	23	26
50	14	14	21	29	36	41
60	18	19	29	42	55	62
70	23	25	39	59	79	>80
females						
20	8	8	9	9	10	12
30	9	9	10	11	12	14
40	11	11	13	15	17	21
50	14	14	18	21	24	31
60	18	19	25	30	35	45
70	23	25	34	41	48	62

Lower decile of an unscreened, typical population without undue exposure to hazardous noise, thresholds in dB relative to young median hearing in an otologically normal population

frequency, kHz	0.5	1	2	3	4	6
age, years						
males						
20	15	10	15	16	27	35
30	16	14	16	32	45	46
40	18	16	25	45	56	55
50	22	20	38	56	64	64
60	29	30	52	66	71	73
70	43	50	65	75	81	84
females						
20	15	8	10	11	12	17
30	19	12	14	15	16	21
40	21	16	20	21	24	31
50	25	20	27	31	34	43
60	33	29	39	43	48	58
70	47	45	55	58	65	72

in the majority of the exposed population. If such a person, with hearing 'at risk', exhibits thresholds which do not breach the decile fence, is there convincing evidence of hearing damage? If the pathogenic factor has not produced HTL's beyond the range of 'normal hearing', the (suspected or alleged) damaged hearing is statistically indistinguishable from normal hearing. If the HTL's are still normal, in spite of known hearing risk factors, then no damage is in evidence.

The Range of Disordered Hearing

A second method of identifying the limits of normal hearing is to separate all humanity into two classes, those whose hearing is plainly normal and those whose hearing is clearly deranged. For extreme cases, the dichotomy between normal and pathological is deceptively obvious. What happens at the boundary, though, if in fact there is an obvious boundary? For those individuals whose category, either normal or pathological, is unclear, there must be a test to decide the appropriate category. In order to make such distinctions, a few terms must be agreed. It is proposed to follow the terminology set out by the WORLD HEALTH ORGANIZATION (1980) as adapted to hearing, and which is widely used in British audiological practice. Disease or other pathogenic influence may result in ...

Hearing impairment, which is any loss or abnormality of hearing function; impairment may be so great as to result in a ...

Hearing disability, which is a restriction or inability to perform some auditory function in the manner or within the range considered normal; if the disability is felt to be of sufficient magnitude, the sufferer may claim to have a ...

Handicap, which is the perceived social disadvantage limiting or preventing the fulfilment of that individual's life-role.

Hearing impairment exists within the hearing organ and should, in principle, be measurable. Loss or abnormality of hearing function might affect frequency selectivity, temporal summation, loudness growth, or indeed any of the complex signal detection and processing functions of the hearing organ. However, the most easily and reliably measured of these functions is hearing sensitivity, in the form of the pure-tone audiogram for each ear. The determination of pure-tone thresholds is a relatively straightforward process which is widely available throughout the country. This may not be the case for any of the more esoteric hearing functions, which must be measured by highly trained audiometricians using specialized instruments to perform hearing tests which make great demands upon the attention and judgment of the subject. Furthermore, there is as yet no standardized body of normative data against which to compare individual results. The simple audiogram is the method of choice to quantify a hearing impairment.

Disability may be the consequence of a hearing impairment, but not an automatic consequence; minor impairment may produce no discernible loss of ability to perceive everyday sounds. However, when an impairment is great enough to produce a hearing disability, the loss of normal function customarily refers to hearing for speech. Hearing disability for speech may be measured if one is willing to make compromises, balancing simplicity of measurement against realism. 'Everyday speech' is a phenomenon of considerable complexity, with different topics, grammar, elocution, varying degrees of redundancy, possibly heard in quiet or in noise which might be a background of other voices; the complications are legion. Speech audiometry is possible if sacrifices may be tolerated - sacrifices of realism and validity, in order to achieve repeatability of measurement, and controllable conditions. The important concept is that hearing disability for speech is susceptible to measurement, albeit with some compromise, in the same way as is hearing impairment. In fact, impairment and disability are directly related although not perfectly correlated.

Going one step further, if a hearing disability is sufficiently serious, it may be perceived to be a handicap by the sufferer; handicap is a feeling of social disadvantage. Such a feeling cannot be directly observed, but instead depends upon self-report (or observation of behaviour) as the means of communication between sufferer and assessor. The self-report must be structured, in order to make an adequate and equitable assessment of the effect of the hearing disability. Such structure implies a questionnaire following a standard form, that is, using a limited number of questions validated as measuring some aspect of perceived social disadvantage, and administered in a repeatable and standardized manner. In some areas of audiology, hearing aid prescription or aural rehabitation for instance, the 'sameness' or predictability of a standard questionnaire is a desirable feature, assisting in the reliable measurement of therapeutic benefit. For use in cases of noise damage to the hearing and the resulting perceived disadvantage, questionnaires invite abuse in the form of exaggerated or blatantly untrue statements about feelings of social problems. Even if self-report of handicap could be trusted as a measurement, is it an appropriate quantity to measure for the assessment of hearing function? An individual's life-role depends upon age, sex, social and cultural status ... in fact, any number of variables completely unrelated to hearing function or hearing damage. If two peple have identical hearing impairments, and one feels himself handicapped, the other not, which of the two should be compensated? Should both? Should either?

In the reviews which follow, emphasis is given to reports or assessment schemes which concentrate on measurable quantities, threshold elevation or speech perception deficit. In fact, some researchers may relate the two, either as independent and dependent variables, or at least as quantities which increase in synchrony. Self-report of handicap is mentioned several times, only to be shown as unsuited for the reliable differentiation between normal and disordered hearing function.

The Reviews

DAVIS (1965)

"Ideally, hearing handicap should be evaluated in terms of ability to hear everyday speech under everyday conditions. The ability to hear sentences and repeat them correctly in a quiet environment is taken as satisfactory evidence of correct hearing for everyday speech. However, because of present limitations of speech audiometry, the preferred procedure is to **estimate the hearing threshold level for speech from air-conduction measurements made with a pure-tone audiometer."** (Emphasis by the committee responsible for the article.) For this estimate of what is nowadays called disability, the simple average of HTL's (re ISO audiometric zero) at 0.5, 1 and 2 kHz is recommended. If the average threshold does not exceed 25 dB, there is "no significant difficulty with faint speech".

WEBSTER et al (1965)

The authors offer comments on a paper by Harris (1965) suggesting that the intelligibility of "everyday speech" may be predicted from a three-frequency average HTL of the listener. The discussion centres not on which frequencies best predict intelligibility, but rather on how to attack the predictor-frequency problem. It is suggested that valid research should be designed around the following conditions:

1. listeners should have high-frequency hearing deficits;
2. the character of the speech-test voices should cover the continuum of enunciation, age, sex and regional accent;
3. the masking noise which is most appropriate and most effective is a background of meaningful speech babble producing the most difficult yet controllable listening situation; and
4. the speech material should be presented at a representative level, which is the same for both normally-hearing controls and test subjects with any degree of hearing deficit.

When stated clearly, these requirements for speech intelligibility research seem obvious. The applicability of research results to everyday people, with everyday hearing problems, depends upon how closely the test conditions mimic real life.

DEPARTMENT OF HEALTH AND SOCIAL SECURITY (1973)

This document addresses the general question whether there are degrees of noise-induced hearing loss which satisfy the conditions set out for prescribed diseases under the National Insurance (Industrial Injuries) Act 1965. For noise deafness to qualify for benefit, three detailed questions had to be answered in the affirmative.

1. Is noise-induced hearing loss a disease within the meaning of the Industrial Injuries Act?
2. Is noise-induced hearing loss a risk of occupation?
3. Can the extent of injury due to occupational noise be distinguished in the individual claimant?

From the evidence relating to each question, it was concluded that occupational hearing loss meets the statutory requirements of a prescribed disease, and that long-term disablement benefit may be paid to those sufferers who qualify.

For compensation purposes, several levels of hearing loss were identified. The lowest of these was the level at which a loss of faculty might be considered to have occurred, that is the point in the gradual development of deafness at which the loss of hearing results in a minimal "disablement" (synonymous for present purposes with disability) of at least 1%. For the loss of ability to discriminate speech, this baseline disablement was set at 40 dB HL averaged over the better-ear thresholds at 1, 2 and 3 kHz. It was recognized that this level was relatively high, but justified in order to reduce the importance of temporary threshold shift at the time of audiological assessment.

The degree of occupational noise disablement at which compensation would be payable was fixed initially at a higher level, 50 dB averaged over the thresholds at 1, 2 and 3 kHz in the better ear. This level was to represent a disablement of 20%. The specification of this relatively severe level of hearing loss was intended to dampen demand on the audiological services of the National Health Service, and to allow time for experience to be acquired in the medical administration of the deafness compensation scheme. It was noted that occupational deafness rarely affects earning power, but was a proper subject for compensation under a scheme based on loss of social faculty.

EWERTSEN and BIRK-NIELSEN (1973)

A questionnaire was devised to reflect patients' hearing handicaps in daily life. The instrument was intended to indicate the influence of hearing handicap upon psychological, vocational and family relationships, without expression of audiometric test results. The questionnaire comprised 21 items, including 3 different situations:

1. conversation with one person, in quiet as well as noisy surroundings, in the home or outside;
2. group conversation; and
3. communication by telephone, radio or television.

The items, which were balanced for positive and negative responses, were answered on a 5-point scale. The responses were summed and normalized to give a Social Handicap Index.

The questionnaire was tested on 223 persons, 25 normally-hearing and 198 hearing-impaired. Social Handicap Index was plotted as a function of speech reception threshold for all subjects; speech reception threshold is the presentation level necessary for 50% correct reception. A positive relation was apparent between the variables, although this relation was not tested by statistical means. The relation between hearing impairment (as measured by the speech reception threshold) and the Index was summarized by the authors:

> "When a person has a serious hearing loss, he surely also has a serious handicap. But a person with only a quantitatively slight hearing impairment may have a handicap of any magnitude, from a very low to a maximum value."

The authors suggest two reasons as to why their relation between impairment and social handicap should be so vague:

1. the Social Handicap Index has something to do with the **quality** of the hearing impairment; and
2. the Social Handicap Index measures something independent of, and distinctly different from, hearing impairment.

Of the arguments offered in support of this particular hearing handicap questionnaire, none inspires confidence in the general proposition that such questionnaires might serve as accurate and equitable assessments of the effect of noise-induced hearing loss.

KRYTER (1973)

In this discussion paper, the author reviewed the methods commonly used for evaluation of hearing impairment and the relation between noise exposure and hearing damage. The discussion was intended to illuminate what the author felt to be significant underestimations of the effect of noise-induced hearing loss, and consequent overestimates of tolerable limits for noise exposure.

The author accepted the use of average HTL at 0.5, 1 and 2 kHz as a practical index of an individual's ability to understand speech. Additional evidence was acknowledged that inclusion of thresholds for higher frequencies, 3 or 4 kHz, might yield a more valid index. It was not the index which the author felt to be in error, but rather the relation between the index, as independent variable, and degree of disability/handicap as dependent variable. Of the arguments offered, only that pertaining to the threshold of disability, the 'low fence', need be presented here. In summary, the author proposed a much more cautious value for the low fence: an average HTL of 15 dB for the frequencies 0.5, 1 and 2 kHz; or 25 dB for the 1, 2 and 3 kHz average. These values were 10 dB lower than the criteria commonly used in the United States, the country to which the argument was directly applicable.

The argument for the more conservative low fence value was based upon the relation between speech reception and average HTL, as formulated in the calculation of Articulation Index, used in communication research and assessment. Curves were presented showing the percentage of sentences correctly heard as a function of average threshold; obviously, the worse the listener's hearing, the smaller will be the proportion of sentences heard. The low fence was defined as that elevated average HTL (15 dB HL) which would put the listener at the very brink of missing some small portion of everyday speech, or as the author stated:

> "... the listener would be just able to understand all simple, unrehearsed sentences when presented to him in quiet at an average intensity level at the listener's position of about 65 dB, i.e., speech at an 'everyday' level (that used in an office, on the telephone, in a group discussion, etc.)"

This 'everyday level' was about 10 dB above that for normal conversation; the curves showed that an average loss of 15 dB HL at 0.5, 1 and 2 kHz was associated with a 2% loss in sentence intelligibility at normal conversational level, 55 dB in quiet surroundings. A person with average hearing at the low fence value would have a more severe disability for the understanding of distorted or slurred speech, speech in the presence of noise, or in a group when several people are speaking at once.

The low fence was reasoned, by the process above, to exist at 16 dB HL for the frequencies 0.5, 1 and 2 kHz, or 26 dB HL for 1, 2 and 3 kHz. Having accepted these values as indicating a just discernible speech disability (2% intelligibility loss), the author proceeded to argue the case for a daily noise exposure limit to implement the disability fence. He proposed that the noise limit should result in an increase in the hearing-disabled population of only 10% from that proportion disabled by the action of age alone. The equivalent, eight-hour-per-day noise exposure level was reasoned to be 55 dB(A). (The comparable, current European value for an 8 hour day is 85 dB(A), 30 dB higher.)

The author recognized the controversial nature of his proposals for a reduced low fence for hearing impairment and a greatly reduced level of tolerable noise exposure. He was of the opinion, however, that data then available permitted a more realistic and objective appraisal of the relation between noise exposure and hearing, and of the value of hearing to individuals and society in general. This concept of the value of hearing is not a scientific or, for that matter, a medical question. Rather, the value judgment is a societal and governmental problem of the degree of hearing disability which may be imposed upon people, in exchange for the benefits of commerce, trade and industry.

The author anticipated that his conclusions and proposals would be disputed; he was not disappointed. The editors chose to publish his article with a number of rebuttals/criticisms immediately following. The passage of time has shown the practical value of the author's proposals: the threshold of hearing disability, at 26 dB HL averaged over 1, 2 and 3 kHz, has gained some acceptance; the proposed limit of 55 dB(A) equivalent 8 hour noise exposure has not.

MERLUZZI and HINCHCLIFFE (1973)

In a study of auditory thresholds in a random sample of a rural UK population, see HINCHCLIFFE (1959a,b), each subject was asked the question "Is your hearing normal, or not as good as it used to be?". The latter alternative was taken to indicate auditory handicap recognized or acknowledged by the respondent.

Audiograms were obtained from 391 subjects, covering the age range 18 to 74 years. A mean threshold level for the frequencies 0.5, 1 and 2 kHz was determined for subjects within age bands. Treatment of individual ears is not discussed; both genders were combined within age groups. Within each subject sub-group, a mean threshold was determined for those subjects reporting subjective handicap ("... not as good ..."). The authors' best representation of the threshold of subjective auditory handicap is given by the expression:

$$\log (\text{mean HL}) = 0.0185 (\text{age}) + 0.145$$

The table below lists what the authors term the threshold of subjective auditory handicap for representative ages,.

age	threshold of handicap
30 yr	5 dB HL
40	8
50	12
60	18
70	28

For the relatively young person, hearing is recognized as "not as good as it used to be" when the average hearing level exceeds quite low values, less than 10 dB HL. A three-frequency average of 26 dB HL, a widely-used threshold of auditory disability/handicap, would be associated with a person aged 68 years. The authors do not suggest that the actual threshold of auditory handicap is age-dependent. Rather, the authors feel it likely that the gradual change of threshold with age is not recognized as a deterioration until a threshold of handicap is breached. In other words, the increasing values of the table simply reflect the widespread expectation of dullness of hearing with advancing years.

MACRAE (1975)

A procedure is presented for determining percentage hearing loss. The procedure, originating from the National Acoustic Laboratories of the Australian Department of Health, categorizes impaired hearing in terms of loss of ability to hear speech in quiet and in noise. (In WHO parlance, this is hearing disability). The categories of degree of loss are slight, mild, moderate, severe and profound, with monaural and binaural categories determined by the HTL of each ear at 0.5, 1, 1.5, 2, 3 and 4 kHz, in relation to ISO audiometric zero.

Of interest here are the HTL values which define the lower boundary of slight binaural loss, above which a person would "have difficulty in hearing and recognizing faint everyday sounds and, in particular, faint speech signals against a background of noise". For present purposes, this boundary would separate normal hearing from minimal disability. Two sets of HTL values are given, one based upon 5 dB intervals of HL, the other upon smaller steps.

frequency, kHz	0.5	1k	1.5k	2k	3k	4k
5 dB steps	15	15	15	15	15	20
steps < 5 dB	18	18	18	18	19.5	22.5

Any person with threshold levels, for both ears, better than or equal to those listed would be considered to have 0% binaural hearing loss, that is, normal hearing with no disability.

BRITISH STANDARDS INSTITUTION (1976)

This British Standard (BS 5330:1976) specifies a relationship between noise exposure and the expected incidence of hearing handicap. An individual would be deemed to have some degree of hearing handicap if the average hearing threshold level at 1, 2 and 3 kHz in both ears is equal to or greater than 30 dB. This definition assumes that the hearing levels in the two ears are "substantially similar". As the Standard is intended to estimate the number of handicapped individuals in a noise-exposed population, rather than the degree of handicap in a noise-exposed individual, no tolerances are set for differences in hearing levels between ears.

The combination of frequencies used here, that is 1, 2 and 3 kHz, conforms with that used by the DEPARTMENT OF HEALTH AND SOCIAL SECURITY (1973 and 1978) for determining the degree of pensionable disability due to occupational hearing loss. Other frequency combinations have been advocated elsewhere, to estimate degree of hearing disability/handicap, but without clearly demonstrable superiority.

TEMPEST (1977)

A discussion is offered of the problems of evaluating hearing handicap, so that a claimant may be placed accurately on a scale, or in a category, which assesses the degree of handicap (or otherwise) for damages or pension. In order to be workable, the scheme must be based upon some easily measured aspect of hearing, must be fair to genuine claimants, but must not be susceptible to significant abuse.

One possible method of assessment depends upon the claimant's own description of his condition and handicap. Such a subjective method can be fair only if a standardized, strictly administered questionnaire is employed. Such a method would seem to be open to abuse.

The alternative method of handicap assessment would use audiometric measurements, either pure-tone threshold determinations or measurements of speech threshold and/or discrimination. At first sight, speech audiometry would appear the more appropriate choice. However, speech audiometry requires specialized equipment and expertise which would limit its availability; standardization of speech material and test presentation also present problems. It would appear that only assessments based upon pure-tone thresholds are both workable and widely available.

The author offers an assessment scheme based upon that proposed by the DAVIS (1965). For hearing losses sufficiently large to be a clear handicap to the sufferer, the scheme categorizes the handicap using the better ear average of the thresholds at 0.5, 1 and 2 kHz. For the determination of normal hearing, this three-frequency average is thought too crude; five frequencies are employed to categorize the "quality" of a person's hearing loss. No significant loss of hearing is deemed to exist if the better-ear average HTL at 0.5, 1 and 2 kHz is less than or equal to 25 dB HL, and the HTL at 4 kHz "and/or" 6 kHz are(is) less than 25 dB HL in the better ear. Once this high-frequency fence is breached, hearing is deemed to be sufficiently impaired so that a slight handicap will be evident for speech heard in noise; the perception of speech under normal conditions will be unaffected. No experimental evidence is offered in support of the new feature of the categorization scheme, that is, the high-frequency test of near-normal hearing. Rather, the scheme is recommended on the basis of its usefulness in compensation negotiations in cases of noise-damage litigation.

HEALTH AND SAFETY EXECUTIVE WORKING GROUP ON AUDIOMETRY (1978)

In its discussion paper **Audiometry in Industry**, the HSE states that the main purpose of industrial audiometry is to monitor quantitatively the hearing status of an individual throughout the period of employment, in order to control the risk of occupational hearing loss. In order to test the success of a hearing conservation programme, individual cases are classified on the basis of audiometric results. Five categories are available, each based upon the hearing threshold levels at 0.5, 1 and 2 kHz (low frequencies) and at 3, 4 and 6 kHz (high frequencies).

Individuals whose hearing deteriorates very quickly over time would be placed in category one. Category two receives cases of right-left difference exceeding criteria for the low- and high-frequency thresholds. Category three indicates that a person's hearing is clearly deficient for his or her age; criteria are set out by age bands, for low and high frequencies. Category four is also age-related, but with criteria not so extreme as for category three. Any case not falling into the first four categories is allotted to category five.

The "designated medical practitioner" or company doctor is responsible for deciding on appropriate action in the case of persons categorized as 1, 2, 3 or 4. For category 5, no action is necessary, as the audiometric results have suggested no problem. Category 5 is indicated if an individual's mean threshold at 0.5, 1 and 2 kHz and mean threshold at 3, 4 and 6 kHz are less than or equal to the values listed below.

	mean thresholds, dB HL	
age, years	0.5, 1, 2 kHz	3, 4, 6 kHz
20-24	15	15
25-29	15	15
30-34	15	15
35-39	16	18
40-44	17	20
45-49	18	22
50-54	19	25
55-59	20	29
60-64	21.7	33.3
65-	23.3	38.3

These mean thresholds, which allow for some deterioration of hearing with age, indicate acceptance of a less-than-ideal criterion, consistent with a balance between industrial hygiene and a noisy workplace. A person falling into category 5 would be deemed to have been adequately protected from noise damage to the hearing. For such an individual, the hearing conservation programme has proved successful; no action is required save continuance of the hearing conservation programme.

It could be said that a hearing conservation programme fulfilling the conditions of this Discussion Document, including the categorization scheme, meets a standard of best, prudent practice as defined by the HSE. Certain provisions of this Document have been adopted as International and British Standards of audiometric practice for hearing conservation purposes; the classification scheme outlined above has not.

DEPARTMENT OF HEALTH AND SOCIAL SECURITY (1978)

This document reviews the operation of the provisions for occupational deafness set out by the DEPARTMENT OF HEALTH AND SOCIAL SECURITY (1973). For the purpose of defining occupational deafness and determining its severity, the hearing thresholds in the middle of the speech range had been chosen originally, in preference to a more direct measure of speech reception. The specification of an average hearing threshold level, for each ear at the frequencies 1, 2 and 3 kHz, was confirmed. However, it was recommended that the qualification for long-term disablement benefit be amended: there should be a permanent sensorineural loss of at least 50 dB HL (averaged over the three frequencies) in each ear, and the loss should be due to occupational noise in at least one ear. Concurrently with this amendment, it was also decided to alter the scale of average hearing loss and degree of disablement. The Industrial Injuries Advisory Council suggested that, should the time come when it is possible to reduce the level at which benefit becomes payable, the scale should recognize that disablement from permanent hearing loss begins at 30 dB HL averaged over the frequencies 1, 2 and 3 kHz.

AMERICAN ACADEMY OF OTOLARYNGOLOGY and AMERICAN COUNCIL OF OTOLARYNGOLOGY (1979)

Guidelines are offered, in the light of then-current information, to physicians responsible for the evaluation of permanent hearing impairment and handicap. For the purposes of this guide, impairment is defined as a change for the worse in either the structure or function of the hearing organs, resulting in a hearing loss. Permanent hearing handicap is the disadvantage imposed by a permanent impairment, sufficient to affect a person's efficiency in the activities of daily living.

The measure of impairment, for each ear, is the average of HTL's determined for 0.5, 1, 2 and 3 kHz. The percent impairment for each ear is then calculated by applying a multiplicative factor to the amount by which the four-frequency average exceeds 25 dB HL.

Once a percentage impairment has been calculated for each ear, binaural handicap is determined by use of the following formula:

$$\text{binaur. hand.}(\%) = \frac{[5 \times \text{better ear imp.}(\%)] + [\text{worse ear imp.}(\%)]}{6}$$

It is clear from this formulation that handicap is felt to be directly related to average HTL; no binaural handicap exists if the four-frequency average HTL is less than or equal to 25 dB HL in each ear.

This scheme is held, by the organizations responsible for its promulgation, to be an improvement upon previous versions. The calculation procedure has been altered, by the inclusion of the HTL at 3 kHz, to correlate more strongly with speech understanding, not only in quiet but also in the presence of noise.

No allowance is made for presbyacusis. It is possible, however, to estimate from other sources at what age a person might become handicapped through age-related hearing loss alone. From the Shipton (1979) tables relating pure-tone thresholds to age, it may be seen that the otologically normal median male or female would not become hearing handicapped, even to a minimal degree, until well past the age of 70 years. For the typical or unscreened population dealt with by ROBINSON (1988a), the median male would become hearing handicapped by age 68, and the median female by an approximate age of 75 years.

BROWNING et al (1980)

An early report is made of a pilot study intended to assess the incidence of self-reported hearing loss and tinnitus in the adult population of the UK, and to confirm audiometrically the validity of the self-reported results. A sample of 522 adults, ranging in age from 18 to 95 years, was randomly selected from the electoral registers of Glasgow. Each member of the sample was sent a postal questionnaire regarding hearing; approximately 80% returned the questionnaire. Of these respondents, 65% reported no hearing loss, 20% some hearing difficulty, and 15% a definite hearing impairment; 50% reported having noises or buzzing in the head.

Of the questionnaire respondents, a random sub-sample attended for a full clinical and audiometric assessment. An individual was considered to have a hearing loss if the HTL's in the better ear were greater than the following values:

frequency, kHz	0.5	1	2	4	6	8
threshold, dB HL	30	25	25	25	40	40

Of those reporting no hearing problems, 10% failed this screen. Of those reporting a hearing problem, 65% failed the screen. This left 35% of those reporting a hearing problem or impairment having measured thresholds less than or equal to the audiometric criteria. The incongruity between questionnaire responses and measured thresholds was not resolved. Nevertheless, these pilot study results suggested to the authors that the incidence of hearing problems was higher than previously anticipated.

COLES and WORGAN (1980)

The authors propose a scheme for the assessment of auditory handicap associated with hearing loss due to noise, with account taken of the loss due to ageing. The scheme is said to apply only to hearing losses due to disorder of the inner ear, and only when that disorder contains a definite and practically significant element of noise-induced hearing loss.

The assessment scheme requires the determination of both a-c and b-c thresholds for 0.5, 1, 2, 3 and 4 kHz, for each ear. An average hearing loss is calculated for each ear, using the a-c thresholds for 0.5, 1 and 2 kHz. Binaural weighted averages are then determined for the three-frequency average and for the 3 kHz and 4 kHz thresholds; for each of the three binaural quantities, the weighting is 4:1 in favour of the better ear value. If the b-c thresholds are more than 10 dB better than the a-c values, the b-c thresholds should be used to calculate the handicap due to disorder of the inner ear.

Using the three binaural weighted averages, the three-frequency average and the averages at 3 kHz and 4 kHz, sensorineural hearing loss is divided into ten classes of auditory handicap. The lowest of these ten is described as no significant degree of handicap, attracting a suggested disability rating at 0%. This 'no handicap' class (? normal hearing) is effectively defined as all thresholds, 0.5 to 4 kHz being less than or equal to 25 dB, for both ears.

The seemingly simple definition of "no significant handicap" is founded upon a computational anomaly. "Any values for the 500-1000-2000 Hz average, or for 3000 Hz or 4000 Hz, that are less than 25 decibels should be counted as 25 decibels (for purposes of calculating ... the binaural hearing loss)." In other words, any hearing levels less than 25 dB may not counteract hearing levels greater than 25 dB. Thus, binaural-weighted average HTL's are not calculated to give a true numerical representation of average hearing, but rather an artificially elevated value.

It should be pointed out that this scheme was originally devised in 1977, with the intention that it be compatible with that of TEMPEST (1977). Neither the original version, nor the revised version (1980) reviewed here, appears to have been published in the open literature. The scheme does seem to have some adherents among otolaryngologists involved in medico-legal assessment in cases of alleged noise-induced hearing damage. Circumspection should be advised, however; the scheme appears not to have been subjected to the customary rounds of editorial and peer review.

WORLD HEALTH ORGANIZATION (1980)

This international body has defined a number of degrees of hearing impairment, based upon the average hearing threshold level for pure-tone frequencies of 0.5, 1 and 2 kHz. The lowest class of impairment, termed mild, has a 'low fence' of 26 dB HL (re ISO 389) in the better ear. Presumably, an average HTL of 25 dB or less is indicative of 'no impairment', which by WHO definitions would imply 'no disability'.

PARVING et al (1983)

Two hundred and six Danish men took part in a cross-sectional hearing survey, with a questionnaire concerning hearing ability and disorders. The men, within the age range 49 to 69 years, were not screened for participation in the study.

The subjects gave a medical and otological history, and were examined otoscopically. From the history and questionnaire, it was determined that 44% of the subjects complained of noticing a hearing impairment. The audiological testing showed that 35% had a hearing threshold level equal to or greater than 25 dB averaged over 0.5, 1, 2 and 4 kHz. The authors remark that these two percentages, 44 ± 7% and 35 ± 5%, compare favourably. No evidence is offered to show that the men complaining of hearing impairment were, in fact, those whose four-frequency average HTL exceeded the "low fence" of 25 dB HL.

PARVING and OSTRI (1983)

In a follow-on study from that reported in PARVING et al (1983), seventy-seven men aged 49 to 68 years were selected for study, out of a larger pool of 206 subjects. The sub-group had all been diagnosed as suffering from noise-induced hearing loss.

From questionnaire responses, 52% (40 of 77 subjects) reported a general impression of subjective hearing disability. The remaining subjects did not report disability. A number of threshold averages and low fences were tried as objective measures to predict disability. The best indicator was found to be a five-frequency threshold average, the HTL's at 0.5, 1, 2, 3 and 4 kHz in the better ear, being equal to or greater than 20 dB. Of the 77 men in the NIHL group, 63 were classified as hearing impaired using the best indicator low fence. Of these 63 impaired men, 34 (54%) had assessed themselves as having a hearing disability. On the strength of this evidence, the authors felt unable to apply an objective indicator to auditory handicap.

ANON. (1983)

Procedural guidelines are described for the quantitative assessment of hearing disability for compensation purposes. These guidelines are described as approved by the British Association of

Otolaryngologists and the British Society of Audiology. The scheme outlined gives a formula by which measurement of hearing impairment, defined as loss or abnormality of hearing function, may be used to give an estimate of hearing disability or restriction of ability to perceive everyday sounds such as speech. For present purposes, the boundary between no disability and some disability is of interest.

The measure of impairment to be considered, for each ear separately, is the average of HTL's determined for 1, 2 and 4 kHz. If a measured HTL is negative (more acute than audiometric zero), a value of zero shall be used for the calculation of the three-frequency average. (Note that this restriction has the effect of making the average always positive, with what might be considered an artificially heightened value.) When the average HTL is less than or equal to 20 dB, there is deemed to be no disability for that ear.

Once a percentage disability is determined for each ear, a binaural disability is calculated from that for each ear by use of the following formula:

$$\text{binaur.disab.}(\%) = \frac{[4 \times \text{better ear disab.}(\%)] + [\text{worse ear disab.}(\%)]}{5}$$

It is clear from this formulation that no binaural disability exists if the three-frequency average is less than or equal to 20 dB HL in both ears.

The scheme recognizes that presbyacusis, the hearing loss associated with age, might reach such a level as to cause a binaural disability. Referring to National Physical Laboratory tables by Shipton (1979), an average loss of 20 dB is quoted for the median, otologically normal male of 66 years and the median, otologically normal female of 74 years (extrapolated by the authors). Starting from these ages, disability increases with the mounting years. For the typical, unscreened population dealt with by ROBINSON (1988a), presbyacusic disability would set in much earlier, at age 56 for the median male, and at age 67 for the median female. The relatively low disability-onset age for unscreened males suggests the possibility that the low fence has been set too low.

COLES, BURNS and KING (1983)

This paper outlines the philosophical, medical and scientific rationales underlying the BAOL/BSA method of assessing hearing disability. The method, see ANON. (1983), was intended to provide a formula by which measurements of hearing impairment, normally an audiogram of a-c pure-tone thresholds, could be used to give an estimate of hearing disability. This latter quantity is calculated on a scale of percentage loss of normal ability to perceive speech.

Pure-tone audiometry provides a measurement method which is widely available for screening and diagnostic investigations, with a high level of standardization of equipment, technique and calibration. In addition, the relation between noise exposure and threshold shift is reasonably well understood. In contrast, measurement of speech reception, in quiet and in noise, would give a direct estimate of disability; hearing questionnaires, likewise, would directly assess handicap. However, neither of these alternative techniques are sufficiently standardized or easily administered to compete with pure-tone audiometry.

The method of determining percentage disability starts with the average of HTL's at 1, 2 and 4 kHz. This particular combination of frequencies is new to United Kingdom practice, the average of 1, 2 and 3 kHz threshold being widely used. The change from 3 to 4 kHz was felt to be justified by the majority of disability assessments in respect of noise-induced hearing loss. For this pathology, maximal threshold elevation occurs most commonly at 4 kHz, but also quite frequently at 6 kHz. Maximal threshold elevation is found only occasionally at 3 kHz.

Having settled upon a particular three-frequency average threshold as the measure of hearing impairment, this measure must be related to a scale of disability. The authors draw upon research results to set the 'low fence', that is, the average HTL corresponding to the transition between no disability and some detectable disability. From research correlating the 1, 2 and 3 kHz average to disability, the results were scaled to the recommended 1, 2 and 4 kHz average; the low fence was correspondingly scaled to give 20 dB HL average HTL.

At the other end of the disability scale, the 'high fence', various average threshold values are discussed, but are not of direct interest here. Similarly, the relation between average threshold and percentage disability does not affect the present interest; having accepted a value for the low fence, we need not be concerned with how hearing might deteriorate from minimal detectable disability to total loss of speech perception.

The authors also consider the problem of mixed impairments. Deterioration of hearing may be expected with increasing age, with an additional, conductive element often present. It was felt that the component of total disability which should be compensated (as in a noise-damage case) is represented by the difference between the overall disability and that attributable to all the non-compensable components combined. Conductive elements are estimated, in individual cases, from the difference between a-c and b-c thresholds. In order to assess the component of hearing loss due to age alone, representative values may be obtained from published sources, for instance Shipton (1979) and ISO 7029. It is not made clear by the authors that these statistics describe the relation of HTL and age for the "otologically normal" subset of the population. The use of these 'ideal' statistics results in a possible overestimation of the compensable disability in an individual case. As age increases, the subset of otological normals becomes progressively smaller, as recognizably pathological incidents, episodes and conditions accrue in the total population. Thus, as age at assessment increases, the probability of overestimation of compensable disability increases to quite high levels. Such a caveat is not found in the discussion of mixed impairments. Since the appearance of the recommended assessment scheme, and the companion paper dealt with here, values have been published which estimate the relation between age and HTL for the typical, unscreened population; see ROBINSON (1988a). Use of values for typical presbyacusis would give a more accurate apportionment of disability components.

The authors express the hope that the new method of disability assessment will prove helpful in cases of noise-induced hearing loss, rather than just another alternative method. Further hope is expressed that the new method will become the usual method of noise disability assessment for common-law compensation claims in the United Kingdom.

Note: It has been announced that the BAOL/BSA disability assessment scheme is under review. The new scheme, which is expected to be greatly revised and expanded, should be made public during 1991/92.

ROBINSON et al (1984)

An investigation was carried out on subjects with mild degrees of noise-induced hearing loss, in an endeavour to identify the points of onset of hearing disability and of hearing handicap. The test group comprised 24 noise-exposed persons of various ages, mean 45 years, with significant but unquantified histories of noise exposure, and free from extraneous otological disorders. Two groups of control subjects were used, one of 20 otologically normal young people and another of 10 older, but still otologically normal, people with mean age 58 years.

A battery of tests was administered to each experimental subject. Pure-tone audiometry, by the self-recording method, was one of five tests of auditory function. Message reception performance was assessed in three simulated real-life situations, including an audiovisual presentation. Speech audiometry was performed at three levels in quiet, and at one level against a background of multi-voice babble. Each subject also completed a questionnaire intended to elicit self-assessments of hearing difficulties and perceived disadvantage, in both general and particular listening situations.

The data were analyzed with a view to distinguishing between people, not between listening situations. By defining a "threshold of inability" in each test as the point corresponding to the 2nd percentile of normal performance (the level below which only 2% of otological normals would fall), the equivalent hearing threshold level was shown to be 30 dB for the 1, 2 and 3 kHz average threshold or 38 dB for the 3, 4 and 6 kHz average, for a general threshold of disability. A similar approach was tried for hearing handicap or perceived disadvantage, with the result that a threshold of handicap is not discernible as a break between the performance of normal and impaired subjects. Instead the authors suggest that, unlike disability, there is a continuum of increasing handicap with no 'low fence'.

SUTER (1985)

An investigation was conducted examining the relation between average hearing level over frequency and speech reception performance, for normal hearing listeners and for those with mild degrees of noise-induced hearing loss. On the basis of average hearing threshold levels at 0.5, 1 and 2 kHz, three subject groups were formed, each comprising 16 individuals: a control or normal group of individuals with an average HTL no worse than 8 dB HL, and no single-frequency HTL from 0.25-6 kHz worse than 20 dB HL; and two test groups, one with the three-frequency average in the range 10-18 dB HL, the other in the range 20-28 dB HL. The two test groups had sloping high-frequency losses typical of noise-induced hearing loss; presbyacusis was held not to be a factor, as the subjects ranged in age from 18 to 56 years.

All subjects performed free-field speech tests monaurally, using the better-hearing ear with the other occluded. Two tests were used: a multiple-choice, closed-set word test; and a sentence test designed to resemble everyday speech. Both tests were performed with the material presented at a speech level of 60 dB(A), in quiet and also against three levels of background 'speech babble' set to give values of speech-to-noise ratio of approximately 0, -3 and -6 dB. (These values may be considered to range from 'unfavourable' to 'very difficult' listening.) Considering the results of the more difficult sentence test, the scores for the control group ranged from 100% down to 58% correct responses for the quiet and -6 dB speech-to-noise conditions, respectively. For the test group with the worse hearing levels, the scores ranged from 94% to 15% correct responses.

To determine which groups of frequencies best predicted speech performance, the reception scores of each hearing-impaired subject were correlated against the average HTL over a number of frequencies. The results of these analyses are summarized below as a table of correlation coefficients.

Correlation coefficients, between speech scores and average HTL's, over all listening conditions

average threshold over frequencies, kHz	correlation coefficient
0.5, 1, 2	-0.54
0.5, 1, 2, 3	-0.77
1, 2, 3	-0.80
1, 2, 4	-0.87
2, 3, 4	-0.86
3, 4, 6	-0.82

The negative sign associated with each correlation coefficient indicates an inverse relationship, viz. higher average threshold ... lower speech scores. The threshold average over 0.5, 1 and 2 kHz was shown to be the poorest predictor of all the averages tried. Significantly better correlation coefficients were found for those averages involving frequencies greater than 2 kHz.

This investigation did not directly address the question of a 'low fence' for the threshold of handicap. The author opined that the selection of a fence is a social issue, which will be influenced by an individual's age, occupation, lifestyle and personal preference. Until more information is forthcoming, from field rather than laboratory studies, any decision on an appropriate low fence value will be somewhat arbitrary. Unmindful of her own caveat, the author suggested that the low fence should be set at 19 dB HL for the 1, 2 and 3 kHz threshold average, or 22 dB HL for the 1, 2 and 4 kHz average.

PARVING et al (1986)

A study is reported, investigating the correlation between hearing threshold level, for single frequencies or averaged over the speech frequencies, and speech discrimination score measured in quiet and in background noise. As a basis for study, Danish noise-damage compensation law was taken as the starting point; if the mean threshold exceeds 20 dB HL for the frequencies 0.5, 1, 2, 3 and 4 kHz (presumably for both ears), a person is deemed hearing-impaired.

One hundred and fifty-eight men, aged 52-72 years, participated in the study. All completed a questionnaire for self-assessment of hearing ability; 36% reported a perceived hearing disability in noisy listening situations, while 64% had no complaints of hearing problems. The men also performed pure-tone audiometry and speech discrimination testing in quiet and in a voice-babble noise (speech-to-noise ratio +10 dB). The hearing tests indicated mild-to-moderate, sloping high-frequency hearing losses for the group; median discrimination scores were relatively high, 88% for the more difficult speech-in-noise listening situation.

Correlation coefficients were calculated for the relation between discrimination score, both in quiet and in noise, and various threshold-frequency averages, over both ears.

Correlation coefficients

average threshold	discrimination score	
kHz	in quiet	in noise
0.5, 1, 2	-0.63	-0.44
2, 4	-0.70	-0.55
1, 3, 4	-0.71	-0.54
1, 2, 3, 4	-0.69	-0.55
0.5, 1, 2, 3, 4	-0.70	-0.54

Note: The negative sign for each correlation coefficient has been added by the present reviewer, to indicate an inverse relationship, that is, higher threshold ... lower discrimination. The authors' omission must be a simple oversight, rather than a computational error.

These results indicate that, of the frequency averages tested, the 0.5, 1, 2 kHz average correlates least well with discrimination score. The other averages, all involving higher frequencies, performed about equally well.

As the five-frequency threshold average, used in Danish compensation law, performed well in the correlation analysis, this scheme was taken further in the analysis. The self-assessments of hearing disability in noise were examined for those subjects above and below the 20 dB HL fence deemed to separate normality from hearing impairment. Of the subjects reporting hearing disability in noise, 70% had a five-frequency threshold average greater than 20 dB HL, that is 70% were deemed to be hearing impaired. This left 30% as false-negatives among the self-reported-disabled. In the group reporting no hearing disability, 34% exceeded the threshold criterion (false positives). On the basis of the high rate of false negatives and false positives, the pure-tone average threshold criterion was judged to be inadequate. The authors recommended further investigations in search of a valid low fence relating to speech discrimination score, which would advance the assessment of hearing disability.

SMOORENBURG (1986)

The author expresses the opinion that hearing disability indices and fences have not been properly justified. In particular, speech perception in noisy situations, although recognized as the situation where hearing difficulties first occur, is insufficiently represented in existing measures of disability. Therefore, a study was undertaken on the perception of speech in quiet and noisy situations, for individuals with noise-induced hearing loss.

Two hundred subjects participated in the study. All were workers in noisy environments, and all were younger than 55 years; the maximum age was chosen by the author in hope of minimizing the possibility of presbyacusis being an unwanted factor in the study. Hearing losses, if present, were chosen to be symmetrical and non-conductive; a wide range of threshold values were present in the subject sample. Speech audiometry was performed using simple sentences, in quiet and in four levels (35, 50, 65 and 80 dB(A)) of speech-shaped noise. No indication is given whether the speech tests were performed by earphone or free-field presentation of the stimuli. Performance was represented by Speech Reception Threshold, that is, the presentation level giving 50% sentence intelligibility.

Speech reception thresholds were correlated against HTL's for individual audiometric frequencies, for the tests in quiet and in noise. For the tests without masking noise, the highest correlations were found for the lower frequencies, 1 kHz and below. For the tests conducted in noise with a speech-shaped spectrum, the reception scores correlated best with the frequencies 2 kHz and above, indicating that these frequencies play the more important role in speech intelligibility in noise.

Correlation coefficients were also calculated to quantify the relationship between speech reception thresholds and hearing thresholds averaged over frequency combinations. For the threshold averaged over 1, 2 and 3 kHz (used for most British applications), correlation coefficients of 0.63 and 0.66 were found for speech in quiet and in noise, respectively. Average hearing loss at 2 and 4 kHz gave a coefficient of 0.72; the author accepted this two-frequency average as a better predictor of speech reception threshold in noise.

Having settled on the average hearing loss at 2 and 4 kHz as a good predictor of speech reception in noise, the author turned to relating a change in average HTL to a change in reception and, thus, a degradation of intelligibility. At an average hearing loss of 10 dB HL, a change of reception threshold was just discernible, implying some loss of sentence intelligibility in noise. The impaired speech reception threshold became statistically distinguishable from normal when the two-frequency average threshold reached 24 dB HL; a sentence-in-noise intelligibility loss of between 30 and 50% is implied by this change in HTL from normal. The author urges the acceptance of the 10 dB HL fence, as a cautious definition of the average threshold defining hearing disability.

The author's suggested fence of 10 dB HL averaged over 2 and 4 kHz must be dismissed as unworkable. Such an average hearing level would be expected at ages 48 and 55 years, in median (50% percentile) otologically normal males and females **without undue noise exposure**; these ages may be derived from the data of Shipton (1979). The 10 dB HL fence may also be viewed in terms of the threshold of a typical population, as seen in ROBINSON (1988a). For such an otologically typical population, containing individuals with adventitious ear pathology, the 10 dB HL average HTL would have accrued by age 36 and 49 years, in median males and females, respectively. For persons as young as 36 years to be described as having a hearing disability, through the influence of age alone, is unacceptable. The application of the 10 dB HL fence in cases of noise-induced hearing loss, as the author intends, cannot be justified.

As a footnote to this review, it should be stated that the author uses the terms disability and handicap interchangeably. It is plain, to this reviewer at least, that the concept being discussed is hearing disability for speech reception.

LUTMAN, BROWN and COLES (1987)

A self-administered questionnaire concerning hearing disability and handicap was completed by 1691 subjects, age range 17 to 89 years, who were part of a random sample of the United Kingdom adult population. Principal components analysis of the questionnaire responses showed that two components were strongest, accounting for 68% of the variance. The first of these was disability for everyday speech, that is, reduced ability for a commonplace task. The second strong component was hearing handicap or psycho-social disadvantage in the individual subject's particular circumstances.

The questionnaire respondents also performed air- and bone-conduction audiometry. For each subject, the better-ear a-c thresholds were summarized according to a two-parameter model of audiogram shape. This model described the audiogram as a flat section, being the average of HTL's at 0.25, 0.5, 1 and 2 kHz, with a slope-like parameter derived from the HTL's for 3, 4 and 6 kHz. The two-parameter model accounted for 89% of the variance in the audiometric data. In addition to the model, each subject's hearing loss was characterized by several binaural indices, computed as a weighted average of HTL's for each ear, with a weighting of 4 : 1 in favour of the better-hearing ear. Four indices were calculated, for: 0.5, 1 and 2 kHz; 1, 2 and 3 kHz; 1, 2 and 4 kHz; and 0.5, 1, 2 and 4 kHz.

Correlation analyses were performed for disability for everyday speech against each index of hearing impairment, also hearing handicap against each index. The binaural index based on 0.5, 1 and 2 kHz was marginally the best predictor of both disability and handicap questionnaire responses, with correlation coefficients of 0.63 and 0.57, respectively. (It should be noted that the 1, 2 and 4 kHz average threshold, see the BAOL/BSA method explained by COLES, BURNS and KING (1983), was not found to be the best predictor of disability.) The slope component of the two-parameter model was clearly the poorest predictor of disability and handicap, with correlation coefficients of 0.20 and 0.24, respectively.

Regression analyses were performed, treating the binaural index based on 0.5, 1 and 2 kHz as the independent variable. Disability responses and handicap response were, in turn, treated as dependent variables. Each analysis gave a smooth, sigmoid function, with no evidence of a natural break between normal and disabled hearing, or normal and handicapped hearing. An alternative approach was undertaken, based upon outliers in the normal subgroup. The authors defined normal-hearing subjects as those having air-conduction thresholds less than 5 dB HL in both ears, at all 8 audiometric frequencies from 0.25 to 8 kHz. Among these normals, there were some outliers who considered themselves to be disabled or indeed handicapped to some degree. The worst 5% of normals gave judgements which, when applied to the regressions, established fences between normal and disabled hearing, and normal and handicapped hearing. In terms of the better-ear weighted average of 0.5, 1 and 2 kHz, the disability and handicap fences were stated to be 15 dB and 13 dB, respectively, for those subjects with a "sloping", sensorineural hearing loss. For those subjects with a "flat" sensorineural loss, the disability and handicap fences were found to be 17 dB and 19 dB, respectively.

COLES and SINCLAIR (1988)

Hearing disorders seldom lead to periods off work. The impact of hearing loss or tinnitus is related more to working efficiency and safety, and the employer's responsibilities for employee health. There are cases where hearing loss may not be compatible with particular employment, for instance, where there is a requirement for good communication ability, e.g. radio operators, or where there is an exceptionally high level of responsibility, as with civil airline pilots. For more ordinary jobs, it is sufficient for the employee to be able to hear what people say in the normal working environment. The authors conclude with the following statements:

> "Normal hearing is difficult to define in terms of either normal function or lack of perceived disability, especially as any definition is essentially arbitrary and may be ambiguous as to whether or not 'normal for age' is intended. There is wide individual variation in the degree to which a hearing impairment causes measurable hearing disability, and to which a hearing disability is perceived by the person affected. Moreover, the effect of a disability in the context of fitness for work depends greatly on the particular job requirement and working environment."

ANON. (1989)

The American Speech-Language-Hearing Association recommends screening to identify persons with a hearing impairment of such magnitude and character as to interfere with daily life. A draft screening protocol is put forward for discussion purposes.

The protocol for hearing handicap/disability comprises two major components. First is an audiometric test to identify persons with a potential medical problem or a loss of hearing sensitivity. For adults aged 18 to 64 years, pure-tone stimuli should be presented by audiometric earphone; the tones should have frequencies of 1, 2 and 4 kHz, with a common level of 25 dB HL. Failure to respond to any of the three stimuli, in either ear, shall constitute a failure of the pure-tone screen. For persons aged 65 years and over, 1 and 2 kHz tones are presented at 40 dB HL; inability to hear either tone in either ear constitutes a failure. For those who pass the 40 dB HL screen, the tones are also presented at 25 dB HL; inability to hear either stimulus in either ear indicates that the elderly person is "at risk" of hearing impairment.

The second component of the protocol is a hearing questionnaire. Two instruments are available: the first asks with what frequency communication difficulties are encountered in various general situations; the alternative questionnaire asks if a hearing problem affects any of a number of common activities. Pass/fail scores are given for each questionnaire.

Screening results, given as pass or fail, depend upon the results for the tone and questionnaire constituents, and are given below for the two age groups.

Screening results for those aged 18 to 64 years

tone	questionnaire	
	pass	fail
pass at 25 dB	Pass	Fail
fail at 25 dB	Fail	Fail

Screening results for those aged 65 years and above

tone	questionnaire	
	pass	fail
pass at 40 dB pass at 25 dB	Pass	Fail
pass at 40 dB fail at 25 dB	At Risk	Fail
fail at 40 dB fail at 25 dB	Fail	Fail

From the overall Pass/Fail conditions set out above, it may be seen that the questionnaire responses take precedence over the audiometric screen. If a person perceives himself to be hearing handicapped in daily life, or if an overall screening failure occurs, the person should be referred for a full audiological evaluation. It should be noted that a screening failure does not confirm the presence of a hearing impairment. It should also be noted that these guidelines are in draft form only, for discussion purposes.

SCHOW et al (1989)

The authors report on the development and use of a scale of Self-Assessment of Communication for estimating the handicap/disability imposed by hearing loss. The self-assessment method advocated is a questionnaire comprising 10 items: six questions categorize systematically the range of spoken communication situations; two deal with the respondent's feelings about communication; the final two items query how other people react to the respondent's hearing abilities. Each question is phrased to require an answer in terms of frequency of communication difficulty, from never to always. Severity or significance of communication difficulty makes no contribution to the score of handicap/disability, only frequency of difficulty contributes.

Research results are summarized to show the relation between self-assessment disability/handicap percentage and level of hearing impairment. Of 1162 people screened at American health fairs, 659 were categorized as normally hearing, defined as giving positive responses to tones of 0.5, 1, 2 and 4 kHz presented at 25, 25, 25 and 30 dB, respectively. The screening is presumed to have been performed by audiometer and earphone, although this is not reported by the authors. For the normal hearing subjects between ages 19 and 79 years, the self-assessment score was approximately 10%; a score of 20% is stated to be the upper limit of normal. For the remaining 503 subjects who failed the hearing screen, only those in the age range 60-89 years gave disability/handicap scores clearly elevated from the 20% normal fence. No satisfactory explanation is offered for the seeming inconsistency between the alternative definitions of "normal", by degree of hearing level and by frequency of communication difficulty. Communication problems may well occur with higher frequency in later life, but what is expected of a disability or handicap measure is some relation to the degree of hearing deficit.

Conclusions on the Thresholds of Disability and Handicap

From the reviews seen here, it is apparent that much emphasis has been placed on disability, that is, the loss of ability to hear and understand speech. However, speech audiometry is not the method of choice to determine speech disability. Instead, pure-tone thresholds are employed in average thresholds used to signify impairments sufficient to cause speech disability. These average thresholds may be over two or more frequencies; listed below are the frequency combinations found in the reviews here.

frequency averages, kHz
2, 4
0.5, 1, 2
1, 2, 3
1, 2, 4
3, 4, 6
0.5, 1, 2, 3
0.5, 1, 2, 4
0.5, 1, 2 (considering 3 or 4)
0.5, 1, 2 (considering 4 and/or 6)

Among the opinions and arguments offered in support of each of the two-, three- or four-frequency averages, only one common factor stands out. In order to be a 'good estimator' of speech disability, a frequency average must employ threshold(s) for pure-tones of 3 kHz or higher. As far as a disability fence is concerned, any value of average threshold between 5 dB HL and 40 dB HL has been put forward; 25 dB HL is the modal value of the sample of fence values seen in the reviews here.

At a slightly higher level are those schemes employing the whole audiogram, as many as six thresholds in each ear. For such schemes, the word 'estimator' is insufficient. One such Australian scheme does not even use averages; threshold fence values are set for six frequencies between 0.5 and 4 kHz, inclusive. Thresholds above the stated values translate into a percentage hearing loss, used to quantify speech disability. Another scheme, set out by the UK Health and Safety Executive, specifies average hearing thresholds for low frequencies (0.5, 1 and 2 kHz) and for high frequencies (3, 4 and 6 kHz). These values, which increase with age, define hearing which is normal for age, or for which no hearing problem should be expected. Both the Australian and British impairment measures have a solid feel to them; the whole audiogram must be measured, for each ear, with honest threshold elevation being the measure used to identify hearing dysfunction.

Hearing handicap, on the other hand, has proved to be a disappointment, to this reviewer at least. Questionnaires used to assay feelings of social disadvantage arising from hearing dysfunction seem to suffer from high rates of false positives and false negatives, simultaneously. This is poor selectivity. The authors of one handicap questionnaire summarize the situation nicely:

> "When a person has a serious hearing loss, he surely also has a serious handicap. But a person with only a quantitatively slight hearing impairment may have a handicap of any magnitude..."

This is the observation of researchers employing experimental subjects, who had nothing to gain from distortion of their own handicap rating. One wonders what ratings would have been observed in a sample of compensation-seekers. Hearing handicap must be condemned as a workable concept; it is of little use in separating normal from disordered hearing, as the concept is based on feeling rather than fact.

SUMMARY DISCUSSION

The differentiation between normal and pathological hearing function rests upon the measured differences between the hearing of the individual in question and the 'book values' for a standard normal person. In the broadest sense, the question facing the clinician, either an audiologist or otologist, is: "To which class of humanity does this patient belong, normal or pathological?". To answer this question, the clinician may make a crude measurement in the form of a subjective impression of the patient's overall hearing performance; this impression is really an ordinal measure of hearing disability ... none, some, a lot. The judgment may be more elegantly stated, with more categories, but the clinical measurement of normal or pathological is still coarse and subjective. The judgment may be supported by history-taking and examination of the ears, nose and throat, but the measurement is little more than an assignment of names ... normal or pathological.

If the patient's hearing function is really quite disordered, the classification is no problem at all; the patient is plainly disabled and therefore abnormal. The real problem, in this case, arises in the diagnosis of the abnormality ... what is wrong, and can it be treated?

If the clinician judges the patient's hearing to be only slightly disordered, or possibly normal, here the situation becomes problematical. The straight-thinking clinician will realize that the variation attached to subjective judgments is simply too great for trustworthy categorization. In other words, subjective impressions are not good enough; better measurements are required. Measurement of pure-tone hearing sensitivity will serve in the present situation. Hearing thresholds may be determined for virtually all patients, using instruments which are widely available and which may be calibrated to recognized standards. Determination of hearing sensitivity may be performed by competent testers who need not have highly specialized training; the patient's task is relatively straightforward and quickly learned.

Once hearing sensitivity is accepted as the measure of choice, in preference to less well-understood phenomena of human audition, the situation may be analyzed piecemeal. As commonly practised, pure-tone threshold audiometry is based upon two measurements: the hearing threshold of the patient; and the modal hearing threshold of the members of an otologically normal population of young people. The difference between these two points is measured in dB HL, and is called the hearing threshold level. The modal threshold of the young otologically normal population forms the audiometric zero, and is free from variation, by definition. The threshold of the patient is, on the other hand, susceptible to variation from a number of sources, both systematic and random.

Systematic variation in the measurement of HTL is that which acts in one direction only, in most cases making the value of hearing threshold level appear higher than it truly is. The threshold elevation may be stable in time, or may be relatively short-lived. One error of the first category is caused by the influence of ambient/environmental noise in the audiometric test space. The noise acts as a masker, interfering with the subject's reception of the intended test tone. The frequency content of most building noise is such that the lower frequency thresholds are most susceptible to noise-masking, typically giving an audiogram with low-frequency droop.

The second or transitory type of systematic error is represented by learning effects and temporary threshold shift. The first of these, learning, is caused initially by unfamiliarity with the audiometric task; practice at the task diminishes the error. The magnitude of the error becomes apparent only on repeat testing; there appears to be no other way of ascertaining which subjects are good at audiometry and which are not. Fortunately, the time scale of learning the task is quite short; over the course of a few minutes, most individuals will become reasonably familiar with and confident at audiometry. The time scale of TTS is not so short, however. The temporary dullness of hearing, resulting from noise exposure before the audiogram, will act as an 'internal masking noise'. Usually TTS will decay over the course of a few hours, allowing accurate HTL's to be determined on the day following noise exposure.

In the consideration of systematic variation of the HTL, one salient point must be grasped: systematic error is a function of testing conditions. The audiometrician who cares about the quality of the data he produces will be aware that choice of audiometric method will influence the final HTL's recorded. The instrument used to obtain these data will have been calibrated to a recognized standard audiometric zero, and that instrument's performance will have been regularly monitored to ensure that the desired level of performance is preserved. As well as the audiometer, the patient's test environment is also a link in the measurement chain. Ambient noise at an appropriately low level within that space will be conducive to the measurement of hearing threshold levels more acute than audiometric zero. Alternatively, ambient noise within the subject's test space may be such that an artificial lower limit is imposed on all HTL measurements performed within that space; in other words, normal or near-normal HTL's may be unachievable.

As systematic error in the HTL is a function of testing condition, the presence, and possibly the magnitude, of such error may be estimated from simple statements of fact. The competent audiometrician will state which audiometric method was employed in the determination of HTL's. Recommended methods of audiometry, if followed, will allow comparison of results between different testers or different test occasions; each method reviewed herein has made provision for immediate repeat tests to show up the effects of learning in the subject. The prudent audiometrician will have his instrument re-calibrated at regular intervals, to recognized standards, and should be prepared to produce the calibration certificates. The prudent practitioner will also be aware of the ambient noise levels within his audiometric booth, and should have documentary evidence to support a claim that the ambient noise is at such a low level as to permit measurement of HTL's at least as low as zero dB HL. An audiometric booth will be a necessity; a "quiet consulting room" will almost certainly influence the hearing threshold levels.

In contrast to systematic variation, random error may act in a positive or negative direction in relation to the final threshold value determined from multiple measurements. Such random error may be associated with the physical conditions of the HTL determination, such as headphone movement between threshold measurements. However, once physical factors have been accounted for, the remaining dispersion must lie in judgment uncertainty within the listener. There is no way to predict this uncertainty for any individual, it can only be determined by observation. Representative figures are available, suggesting that for the population, HTL's at 1, 2 and 3 kHz are subject to less within-subject variation than are the thresholds at more extreme frequencies. However, these values describe the performance of the hypothetical middle person, not the person under test. For the individual under assessment, there is only one way of knowing the degree of uncertainty which is associated with the HTL for each frequency in each ear: repeatability may only be assessed by repeat audiograms. A single determination only provides a threshold estimate of unknown accuracy.

Having examined the errors involved in the determination of HTL's for any person undergoing audiometric examination, the discussion must also touch on the audiometric zero, the baseline against which any specific individual is compared. The audiometric zero is founded upon the distribution of hearing sensitivity found in the young, otologically normal population. This group is defined as composed of persons in a normal state of health, who are free from all signs or symptoms of ear disease and obstructing wax in the ear canals, and finally, who have no history of undue noise exposure. A number of hearing surveys have been conducted to define the hearing sensitivity of otologically normal samples covering a wide age range. However, only the younger members of the normal population have contributed to the audiometric zero. Modal values of hearing sensitivity, for a number of pure-tone frequencies, have been chosen by international consensus to represent normal hearing. The zero values are not universal to all humanity, but are instead technical realizations dependent upon a specific earphone pattern working into a closely-defined electro-acoustic measuring device.

Subsequent to the standardization of audiometric zero, a number of further hearing surveys have been conducted for various purposes. The results of these further studies of otologically normal hearing have been collated as a check on the agreed audiometric zero. From the HTL's determined from over 2500 young, healthy ears, an overall trend may be discerned. For the audiometric frequencies 0.5 to 4 kHz, the presently standardized audiometric zero is a close representation of the hearing sensitivity of normal ears (as determined using the earphone pattern most common to British audiometric practice). Errors about 0 dB HL are small, and are both positive and negative in sign. In contrast, however, the standardized zero values for 0.25, 6 and 8 kHz are such that young, healthy ears appear to have small but systematic hearing losses. At 6 kHz, the systematic error is largest, approaching 5 dB. This error will be present in all audiograms, measured anywhere in the world where the ISO audiometric zero obtains, including the UK.

It has also been observed that the distribution of hearing levels about audiometric zero is not perfectly Gaussian. Instead, the distribution is slightly skewed, with higher values of positive hearing threshold level than would be expected if HTL were an entirely random variable. This skewness suggests that a systematic influence is at work, even in the hearing of young people screened for otological normality. It is suggested that this influence is undiscovered pathology of some sort - either genetic influence, unreported disease or the result of unrecognized hazardous activity. The ISO definition of normality has, after all, a minimal number of exclusions, and could hardly be taken as an exhaustive 'hearing health' examination.

In the available literature, it is seen that there exist a legion of signs, symptoms, historical episodes and hazardous activities which place at risk a person's claim to otological normality. These influences may be allotted to three groups, the first of which is local to the ears themselves. Any sign or report of ear disease obviously indicates non-normality. The second group of influences may be found in the medical history. An individual's genetic constitution, determined at conception, may contain some otological or auditory mischance.

Once this major hurdle is surmounted, then the risk of disease must be faced at every stage of life, in utero, during childhood and throughout adulthood. A number of diseases or happenings have been documented to have a destructive effect upon the hearing of some sufferers. The implication is that all sufferers are at some risk of hearing dysfunction. The final group of hearing risk factors is found in a person's activities. Exposure to impulsive or explosive sounds is known to cause a form of noise-induced hearing loss, perhaps not noticed at the time. Innocent recreations may also involve noise exposure; attendance at popular music concerts is an obvious example.

In the discussion of hearing risk factors, it must be realized that the pathogenic effect of any factor may not be instant and is scarcely ever total. One must be prepared for a continuum of effect, from subclinical hearing loss to severe loss, even total destruction of the hearing. At the low-loss end of the continuum, the hearing deficit may be so small as to be indistinguishable from normal. This overlapping is the area of interest for present purposes; the intention is to separate individuals with minimal hearing deficit from those who are truly normal but simply possessed of hearing on the wrong side of average, through statistical bad luck.

In young people, classification as otologically normal or otherwise requires close inspection and close questioning. The result of incorrect classification is, however, of only small consequence over the population; this is seen as a slight skewing of the hearing threshold level distribution towards higher values. For older people, the situation is of a different complexion altogether. In the older population, otological normality becomes less common, even to the point of exceptionality, as adventitious hearing loss accrues with the passage of time. Such losses may be the result of multiple causes, for example being the result of infection combined with some systemic disease overlaying some hazardous leisure-time activity. With the older individual, the contrast between otologically normal (highly screened) and otologically typical (unscreened) may amount to tens of decibels of hearing level.

If it is accepted that a seemingly otologically normal population contains a proportion of individuals with obscure hearing risk factors, certain questions must be asked. At what point does an individual accumulate sufficient hearing risk to cease being 'normal'? If not normal, what is such a person? At what level of accumulated risk do the majority of individuals lose their normality? If most individuals lose the right to call themselves otologically normal, is audiometric zero a realistic standard when dealing with the majority of humanity?

These questions about the fall from otological 'grace' may best be dealt with by consideration of a new class of the hearing population - typical. The otologically typical population would contain otologically normal individuals of all ages, and also other individuals with the customary, expected accumulation of hearing risk factors accruing with age. The otologically typical population would comprise individuals who may or may not have had episodes of ear disease, who may or may not be suffering from any, or indeed several, of the systemic diseases known to affect hearing function, and who may or may not have engaged at some time in hearing-hazardous activities. However, the otologically typical population should not contain individuals exposed to high-level occupational noise; noise-damaged hearing is not an accepted risk of life, or a usual state of human health.

From studies reported in the literature, it may be concluded that the typical population exhibits hearing thresholds which are on average less acute than those found in the otologically perfect population. The typical thresholds are also seen to be more widely dispersed, in other words more variable, than the normal (perfect) population. It may be argued, with some force, that the typical population should be the standard of expected hearing with age. The typical population represents the reasonable expectation of hearing health for the majority of adults, and as such also represents a fair standard against which to judge noise-damaged hearing. However, it is more difficult to give a definition of "typical" than of "otologically normal"; the concept is dependent upon ethnic, socioeconomic, health and other rather intangible variables.

Another factor bearing upon the fair standard against which to judge hearing loss, of any origin, is the age of the sufferer. It is well documented that degeneration of the hair cells and nerve cells within the cochlea leads to loss of threshold sensitivity. This change of threshold is a natural consequence of growing old. The cell losses, however, start at quite a young age; hair cell degeneration has been observed in cochleae of children and adolescents. However, loss of function due to such histopathology does not usually become apparent until the fifth or sixth decade of life.

The typical pattern of presbyacusis, or age-related hearing loss, involves the deterioration of high-frequency sensitivity. The very highest frequencies are lost first at a relatively young age; this takes the form of an apparent narrowing of the frequency range of hearing. Only in the 40's and 50's does this loss of threshold sensitivity intrude into the usual audiometric frequencies. Males have been shown to lose their high-frequency sensitivity at a faster rate than females. This is thought to result from greater social and recreational noise exposure suffered by males, and certain systemic diseases which show a sex-linked prevalence, e.g. hypertension, arteriosclerosis and atherosclerosis. There are no therapeutic measures for presbyacusis; once these natural age-related changes are established in an individual, they remain as a symmetrical and progressive sensorineural hearing loss.

The age of onset and rate of onset of presbyacusic hearing loss may not be predicted for any individual. There are, however, British and International Standards which give the expected dispersion of hearing threshold by frequency, as a function of age and sex for the otologically normal population. However, it has been argued that this otologically perfect population is not a fair and reasonable standard against which to judge the hearing of adults with respect to age. With the accumulation of age, the adult population also accumulates adventitious hearing loss through the stresses and diseases typical to Western industrial society. There are data available to show the natural loss of hearing sensitivity as a function of age and sex for the typical, as opposed to the otologically normal, population. Although not to the stage of standardization, these typical data show the same loss of high-frequency hearing sensitivity observed in the normals, although at a somewhat accelerated rate.

The loss of high-frequency threshold sensitivity is not the only dulling of hearing faculty to be expected with increasing age; degradation of speech understanding ability will accompany, and later come to dominate, the sensitivity loss. In the early stages of age-related hearing changes, speech discrimination loss is broadly predictable from the elevation of hearing thresholds. This relation between pure-tone threshold and speech disability is common to a number of hearing loss types, including noise-induced hearing loss. However, presbyacusis is a progressive disorder, involving more and more cell degeneration at ever-higher levels of the auditory pathways. As early in age as the 40's, speech discrimination difficulties will be noticed, especially in poor listening environments. This new type of hearing problem, new to the sufferer that is, will be the first manifestations of slowing of the central auditory processes. As time progresses, both cochlear and central auditory dysfunction will increase, to give an acceleration of speech-hearing difficulties during the 60's. The cochlear and central dysfunctions may progress at different rates, in the extreme case giving some considerable speech-hearing disability with very little threshold shift.

It must be stressed that deterioration of threshold sensitivity and, more importantly, speech reception are natural ageing processes, occurring in all individuals to some degree. These senescent changes neither confirm nor deny other forms of hearing loss. Age-related hearing loss may occur in parallel with other conditions, or indeed stand alone without other otological disorders. Reports linking noise exposure and speech reception difficulties in an individual must not be viewed as a statement of cause and effect. Without threshold shift, the joint occurrence of noise and discrimination loss is no more than circumstance. The straight-thinking hearing specialist will realize that, with age-related changes, a severe hearing disability can exist when the overall amount of hearing sensitivity loss is not great. He will also realize that two individuals with the same amount of age-related pure-tone loss may differ significantly in their perception abilities for speech. Noise need not enter the equation.

The link between noise exposure and speech reception difficulty becomes even more tenuous when one considers the newly-named condition Obscure Auditory Dysfunction. This condition is defined by the conjunction of significant speech discrimination difficulty, particularly in everyday noise, with essentially normal pure-tone hearing threshold levels. This syndrome, which occurs even in young people, has been estimated to account for approximately 5% of adult referrals to ENT clinics in the UK.

The problem of age-related deterioration of pure-tone sensitivity and speech discrimination continues to echo through the mind when one turns to the problem of establishing limits to normal or typical hearing. If one is to make a reasoned and supportable judgment as to whether an individual's hearing is normal or minimally damaged due to some pathogenic influence such as noise, expectations of hearing function must be relaxed to account for age. Relaxations must also be made for effects of hearing risk factors typically accumulated with increasing age.

At any age, there exists a boundary between hearing function which might be reasonably expected and that which could be recognized as disordered; this boundary may be defined in three ways. In the first instance, some pathogenic influence may result in a hearing impairment, which is any loss or abnormality of hearing function. For convenience and simplicity, loss of pure-tone threshold sensitivity is taken as the indicator of impairment occurring in the hearing organ. A second concept builds upon simple impairment; a hearing disability is a restriction or inability to perform some auditory function in the manner or within the range considered normal (should be read as normal-for-age). Disability may be a consequence of a hearing impairment, but it need not be an automatic consequence. Minor impairment may produce no measurable inability to perceive everyday sounds. However, when an impairment is sufficient to be recognized as a hearing disability, the loss of normal function customarily refers to loss of speech-hearing ability. Such a 'loss of ability' must be judged against reasonable expectation for age.

The third and final concept for differentiating between expected, usual or typical hearing function and disordered hearing function is that of handicap. If a hearing disability is sufficiently serious, the sufferer may perceive himself to be at a social disadvantage. This disadvantage is a feeling, a judgment by the sufferer of how much more completely he could fulfill his life-role if not afflicted with the hearing problem.

The hierarchy here should be plain. Disease or some other pathogenic agent may produce a hearing impairment. If the impairment is of sufficient degree, a hearing disability may result. If the disability is serious, a feeling of handicap may follow. There exists a parallel hierarchy of measurements of these phenomena. Loss of pure-tone sensitivity is commonly accepted as the measure of impairment. Speech audiometry would be the measure of choice to quantify speech discrimination loss and thus speech disability. However, speech audiometry is not yet sufficiently standardized to give an accurate and repeatable measure of disability, so the pure-tone threshold must serve here as well. To quantify hearing handicap, the only practicable measurement method is self-report using a standardized questionnaire administered in a standardized fashion. Handicap questionnaires suffer from two fatal flaws, however: questionnaires are open to abuse in compensation cases; and questionnaires have been shown to lack selectivity, that is, they give high false-positive and false-negative rates simultaneously.

So the differentiation between damaged and undamaged hearing must stand or fall upon hearing threshold levels. The threshold at each frequency will show the hearing function to be unimpaired or, alternatively impaired to such a degree as to probably cause a speech-hearing disability. Any number of arbitrary schemes exist, each intended to place an individual (or ear) in one of two classes: unimpaired and able; or impaired and thus disabled. It might be argued that any number of arbitrary schemes simply signals the fact that a single reliable, reasonable and equitable classification scheme has yet to be devised. In truth, if the best has not evolved, is there a best scheme at all? Until such a consensus is achieved, a compromise is suggested. Consider the distribution of hearing thresholds over frequency for the typical population. At each age, there will be a threshold level dividing the worst-hearing 10% of the population from the others. If, at any frequency, the 10% typical level is breached, it may be reasonably assumed that some non-typical pathogenic influence or agent has been at work on the individual's hearing. As the suggested dividing line is proposed to be a fractile of the population, the actual threshold levels will increase with age to reflect the expectation of diminishing hearing ability in the typical population not exposed to damaging noise. Any threshold elevation breaching the 'fractile-fence', which has a built-in age-compensation, could then be deemed to indicate the existence of a speech-hearing disability.

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APPENDIX

This Appendix gives values of age-related hearing loss for the audiometric frequencies 0.5 to 6 kHz. Values are given for two types of populations, one screened for otological normality (Tables N1 - N6), the other a typical unscreened population (Tables T1 - T6). Within each population, the tables list hearing levels for males and females.

The data of each table is expressed as hearing level in dB relative to that of the median (50%) of the otologically normal population at a baseline age. For the normal population, extracted from ISO 7029-1984 (also published as BS 6951:1988), the baseline age is 18 years. For the typical population, taken from ROBINSON (1988a), the baseline age is 20 years. The difference in baseline age is of no practical significance.

Table N1

Age-related hearing loss at 0.5 kHz for otologically normal male and female populations, expressed as hearing level in dB relative to median normal hearing at age 18 years

Age (years)	5%	10%	25%	50%	75%	90%
			Males			
20	10	8	4	0	-3	-6
25	10	8	4	0	-3	-6
30	11	9	5	1	-3	-6
35	12	9	5	1	-2	-6
40	13	11	6	2	-2	-5
45	15	12	7	3	-1	-5
50	16	14	9	4	-1	-4
55	18	15	10	5	0	-4
60	21	18	12	6	1	-3
65	23	20	14	8	3	-2
70	26	23	16	10	4	-1
			Females			
20	10	8	4	0	-3	-6
25	10	8	4	0	-3	-6
30	11	9	5	1	-3	-6
35	12	9	5	1	-2	-6
40	13	11	6	2	-2	-5
45	15	12	7	3	-1	-5
50	16	14	9	4	-1	-4
55	18	15	10	5	0	-4
60	21	18	12	6	1	-3
65	23	20	14	8	3	-2
70	26	23	16	10	4	-1

Table N2

Age-related hearing loss at 1 kHz for otologically normal male and female populations, expressed as hearing level in dB relative to median normal hearing at age 18 years

Age (years)	5%	10%	25%	50%	75%	90%
			Males			
20	10	8	4	0	-3	-6
25	10	8	4	0	-3	-6
30	11	9	5	1	-3	-6
35	12	10	6	1	-2	-6
40	13	11	7	2	-2	-5
45	15	12	8	3	-1	-5
50	17	14	9	4	0	-4
55	20	16	11	6	1	-3
60	22	19	13	7	2	-2
65	25	22	16	9	3	-2
70	29	25	18	11	5	0
			Females			
20	10	8	4	0	-3	-6
25	10	8	4	0	-3	-6
30	11	9	5	1	-3	-6
35	12	10	6	1	-2	-6
40	13	11	7	2	-2	-5
45	15	12	8	3	-1	-5
50	17	14	9	4	0	-4
55	20	16	11	6	1	-3
60	22	19	13	7	2	-2
65	25	22	16	9	3	-2
70	29	25	18	11	5	0

Table N3

Age-related hearing loss at 2 kHz for otologically normal male and female populations, expressed as hearing level in dB relative to median normal hearing at age 18 years

Age (years)	5%	10%	25%	50%	75%	90%
			Males			
20	12	9	5	0	-4	-7
25	13	10	5	0	-4	-7
30	14	11	6	1	-3	-7
35	15	12	8	2	-2	-6
40	18	15	9	3	-1	-6
45	21	17	12	5	0	-5
50	24	21	14	7	2	-4
55	29	24	17	10	3	-2
60	33	29	21	12	6	-1
65	39	34	25	16	8	1
70	45	39	30	19	11	3
			Females			
20	11	9	5	0	-4	-7
25	12	9	5	0	-3	-7
30	13	10	6	1	-3	-6
35	14	11	7	2	-2	-6
40	16	13	8	3	-1	-5
45	19	15	10	4	0	-5
50	22	18	13	6	1	-4
55	25	21	15	8	3	-2
60	29	25	18	11	4	-1
65	34	29	22	13	7	0
70	39	34	26	16	9	2

Table N4

Age-related hearing loss at 3 kHz for otologically normal male and female populations, expressed as hearing level in dB relative to median normal hearing at age 18 years

Age (years)	5%	10%	25%	50%	75%	90%
			Males			
20	13	10	5	0	-4	-8
25	14	11	6	1	-4	-8
30	16	13	7	2	-3	-7
35	19	15	10	3	-2	-6
40	22	19	13	6	0	-5
45	27	23	16	8	2	-3
50	33	29	21	12	5	-2
55	40	35	26	16	8	1
60	48	42	32	20	11	3
65	57	50	39	25	15	6
70	67	59	46	31	19	9
			Females			
20	12	9	5	0	-4	-7
25	13	10	5	0	-4	-7
30	14	11	6	1	-3	-7
35	16	13	8	2	-2	-6
40	18	15	10	4	-1	-5
45	21	18	12	6	0	-4
50	25	21	15	8	2	-3
55	30	25	18	10	4	-2
60	35	30	22	13	6	0
65	41	35	26	17	9	2
70	47	31	31	20	12	4

Table N5

Age-related hearing loss at 4 kHz for otologically normal male and female populations, expressed as hearing level in dB relative to median normal hearing at age 18 years

Age (years)	5%	10%	25%	50%	75%	90%
			Males			
20	14	11	6	0	-5	-9
25	15	12	7	1	-4	-8
30	18	14	9	2	-3	-7
35	22	18	12	5	-1	-6
40	27	23	16	8	1	-4
45	34	29	21	12	4	-2
50	42	36	27	16	8	0
55	52	45	34	22	12	3
60	63	55	42	28	17	7
65	75	66	52	35	22	11
70	89	79	62	43	28	15
			Females			
20	13	10	5	0	-4	-8
25	14	11	6	0	-4	-8
30	15	12	7	1	-3	-7
35	17	14	9	3	-2	-7
40	20	16	11	4	-1	-6
45	24	20	14	7	1	-4
50	29	24	17	9	3	-3
55	34	29	21	12	5	-1
60	40	35	26	16	8	1
65	47	41	31	20	11	3
70	55	48	37	24	14	5

Table N6

Age-related hearing loss at 6 kHz for otologically normal male and female populations, expressed as hearing level in dB relative to median normal hearing at age 18 years

Age (years)	5%	10%	25%	50%	75%	90%
			Males			
20	16	12	7	0	-5	-10
25	17	14	8	1	-4	-9
30	20	16	10	3	-3	-8
35	25	20	13	5	-1	-7
40	31	26	18	9	2	-5
45	38	33	23	13	5	-3
50	48	41	30	18	9	0
55	58	51	38	25	14	4
60	71	62	48	32	19	8
65	84	75	58	40	25	12
70	100	89	67	49	32	17
			Females			
20	15	12	6	0	-5	-9
25	16	12	7	1	-4	-9
30	18	14	8	2	-4	-8
35	21	17	11	4	-2	-7
40	25	21	14	6	0	-6
45	30	25	17	9	2	-4
50	36	31	22	12	5	-2
55	43	37	27	16	8	0
60	51	45	34	21	11	2
65	61	53	41	27	15	5
70	71	62	48	32	20	9

Table T1

Age-related hearing loss at 0.5 kHz for typical unscreened male and female populations, expressed as hearing level in dB relative to median normal hearing at age 20 years

Age (years)	5%	10%	25%	50%	75%	90%
			Males			
20	20	15	10	4	0	-3
25	20	16	10	4	0	-3
30	21	16	10	5	1	-3
35	22	17	11	5	1	-2
40	23	18	12	6	1	-2
45	26	19	13	7	2	-2
50	29	22	14	8	3	-1
55	34	25	16	10	4	0
60	40	29	19	11	5	1
65	47	35	22	13	7	2
70	57	43	25	15	9	4
			Females			
20	19	15	10	5	1	-2
25	23	17	11	5	1	-2
30	25	19	12	6	2	-1
35	27	20	13	7	2	-1
40	28	21	14	8	3	-0
45	30	23	15	9	4	-0
50	33	25	17	11	5	1
55	38	28	20	12	7	2
60	45	33	22	14	8	4
65	56	39	26	17	10	5
70	71	30	30	20	12-	7

Table T2

Age-related hearing loss at 1 kHz for typical unscreened male and female populations, expressed as hearing level in dB relative to median normal hearing at age 20 years

Age (years)	5%	10%	25%	50%	75%	90%
			Males			
20	14	10	5	2	-1	-4
25	17	13	7	2	-1	-4
30	19	14	8	3	-1	-4
35	21	15	9	3	-0	-3
40	23	16	10	4	0	-3
45	26	18	11	5	1	-2
50	30	20	12	6	2	-1
55	36	24	14	18	3	0
60	42	30	18	10	4	0
65	51	38	22	12	5	1
70	61	50	28	15	6	2
			Females			
20	10	8	4	2	-2	-4
25	15	10	5	2	-2	-4
30	19	12	6	3	-1	-4
35	21	14	7	3	-1	-4
40	23	16	9	4	-0	-3
45	26	18	10	5	1	-3
50	29	20	12	6	2	-2
55	35	24	14	8	3	-1
60	43	29	18	10	5	0
65	54	36	22	13	6	1
70	69	45	27	16	8	3

Table T3

Age-related hearing loss at 2 kHz for typical unscreened male and female populations, expressed as hearing level in dB relative to median normal hearing at age 20 years

Age (years)	5%	10%	25%	50%	75%	90%
			Males			
20	20	15	8	3	-1	-4
25	20	15	8	4	-0	-4
30	23	16	10	4	0	-4
35	28	20	11	5	1	-3
40	34	25	14	6	2	-3
45	41	31	17	8	3	-2
50	49	38	22	11	4	-0
55	56	45	27	14	7	2
60	63	52	34	18	10	4
65	69	59	42	24	13	7
70	73	65	51	30	18	10
			Females			
20	14	10	6	2	-2	-4
25	17	12	7	3	-1	-4
30	20	14	8	4	-1	-4
35	24	17	10	5	-0	-3
40	28	20	11	6	1	-2
45	32	23	14	7	2	-2
50	38	27	16	9	4	-0
55	44	32	20	11	5	1
60	51	39	24	14	7	2
65	59	46	30	17	10	4
70	69	55	36	22	13	6

Table T4

Age-related hearing loss at 3 kHz for typical unscreened male and female populations, expressed as hearing level in dB relative to median normal hearing at age 20 years

Age (years)	5%	10%	25%	50%	75%	90%
			Males			
20	27	16	9	4	-1	-5
25	37	24	12	4	-0	-4
30	45	32	15	6	1	-2
35	52	39	20	8	2	-1
40	57	45	26	12	4	-0
45	61	51	33	16	6	1
50	64	56	39	21	9	2
55	68	61	46	27	13	5
60	73	66	53	34	18	8
65	78	70	58	42	24	12
70	85	75	63	51	32	18
			Females			
20	16	11	6	2	-1	-4
25	18	12	7	3	-1	-4
30	21	15	8	4	0	-4
35	25	18	10	5	1	-3
40	31	21	12	6	2	-3
45	36	26	15	8	3	-2
50	43	31	18	10	4	-0
55	50	36	22	12	6	1
60	57	43	27	16	8	3
65	64	50	33	20	11	4
70	70	58	41	26	14	6

Table T5

Age-related hearing loss at 4 kHz for typical unscreened male and female populations, expressed as hearing level in dB relative to median normal hearing at age 20 years

Age (years)	5%	10%	25%	50%	75%	90%
			Males			
20	43	27	12	4	-1	-4
25	51	37	18	7	1	-3
30	57	45	24	10	3	-2
35	62	51	31	14	5	-0
40	66	56	37	19	8	2
45	69	60	43	24	11	4
50	71	64	48	30	14	7
55	75	67	54	36	19	10
60	79	71	59	43	25	14
65	85	75	64	49	31	19
70	93	81	68	56	40	24
			Females			
20	16	12	6	1	-3	-5
25	21	14	7	2	-2	-5
30	25	16	9	4	-1	-4
35	30	20	11	5	1	-4
40	35	24	13	7	2	-3
45	40	29	17	9	3	-1
50	46	34	21	12	5	0
55	53	41	26	15	7	2
60	60	48	32	19	10	4
65	67	56	39	24	23	7
70	75	65	48	31	17	9

Table T6

Age-related hearing loss at 6 kHz for typical unscreened male and female populations, expressed as hearing level in dB relative to median normal hearing at age 20 years

Age (years)	5%	10%	25%	50%	75%	90%
			Males			
20	49	35	15	6	-2	-7
25	54	41	19	7	-1	-6
30	58	46	23	8	0	-5
35	62	51	28	11	2	-4
40	66	55	34	15	5	-2
45	70	59	40	20	8	1
50	73	64	46	26	13	4
55	78	68	53	33	18	9
60	83	73	59	41	25	13
65	88	78	66	49	32	19
70	95	84	72	58	41	26
			Females			
20	25	17	9	2	-3	-7
25	27	19	11	5	-2	-6
30	30	21	12	6	-0	-5
35	35	25	15	8	2	-4
40	41	31	18	10	3	-2
45	48	37	22	12	5	-0
50	55	43	27	15	8	2
55	62	50	33	19	10	4
60	69	58	39	24	14	7
65	74	65	47	30	18	10
70	78	72	57	39	24	14