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The limited accuracy of bone-conduction audiometry: its significance in medicolegal assessments

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Abstract
Accurate bone-conduction testing with masking is always difficult, but for clinical purposes limited accuracy suffices. However, when assessing claimants for compensation, extreme care is needed since even small apparent air-bone gaps are sometimes translated into financial abatement. This paper sets out the stringent test conditions required to achieve adequate precision. It also indicates the inaccuracies inherent in such tests, and recommends procedures for interpreting the significance of bone-conduction thresholds.

Introduction

The limited accuracy in bone-conduction (BC) audiometric measurements as well as the inherent biological variability are often not fully appreciated. This has sometimes led otolaryngologists and industrial medical officers to pay unjustified regard to small air-bone gaps and thereby to consent to or recommend over-zealous use of BC thresholds in assessment of noise-induced hearing impairment (hearing loss) and disability. This has led to the same sort of misunderstanding, evident in the stance taken by some employers or their insurance companies when faced with compensation claims. It is also evident in at least one frequently-used setttlement scheme.

The purpose of this paper is to point out these limitations, and to quantify them as far as possible. However, it should be pointed out that recognition of some of these limitations is not new in the field of noise-induced hearing loss compensation in this country. In the Government's scheme for Occupational Deafness, air-bone gaps of 10 dB or less are disregarded. Its notes for doctors on this issue read as follows: 'If the air-bone gap averaged over the 1, 2 and 3 kHz frequencies exceeds 10 dB, bone conduction thresholds should be used to indicate the hearing threshold due to sensorineural impairment and to determine diagnosis' (DHSS, 1979).

Further, in 1983 the British Association of Otolaryngologists and the British Society of Audiology jointly recommended: 'Significant non-compensable components other than due to presbyacusis should be clearly established. Allowing for normal variability of pure-tone threshold determinations and other uncertainties, any such non-compensable component should be at least 20 dB, averaged across 1, 2 and 4 kHz, before it can be regarded as significant. Where any such component is less than 20 dB, it should be disregarded in calculation of the non-compensable disability. In the case of conductive components particular care is needed. Where possible the presence of an air-bone gap should be substantiated by clinical signs of major middle-ear pathology or by absence, or atypical quality, of acoustic reflexes.'

Inherent measurement uncertainty

Both air-conduction (AC) and bone-conduction (BC) measurements have considerable degrees of associated uncertainty. Robinson and Shipton (1982) found standard deviations typically of about 5 dB and 8 dB for AC and BC threshold measurements respectively for groups of young subjects with normal hearing. The variability of the associated air-bone gap values had an intermediate standard deviation of about 6 dB. In the National Study of Hearing (MRC Institute of Hearing Research, to be published), the standard deviation of air-bone gap measurements averaged across three frequencies was found to be around 5 dB. Thus, the upper 95% confidence limit is in the region of 10 dB. These were determinations under laboratory conditions where the major factor was the inherent variation amongst individuals: in everyday clinical conditions the uncertainty is likely to be substantially greater.

Audiometric calibration considerations

British Standard 5966: 1980 for audiometers allows acoustic output tolerances of ± 3 dB in the 0.25–4 kHz frequency range. Thus, with an audiometer conforming to the standard, the actual AC output could be as much as 3 dB less intense than the nominal level and the BC output as much as 3 dB more intense, unless the instrument calibration is known more accurately and allowed for. This could lead to an artificial increase in apparent air-bone gap by as much as 6 dB, in the most extreme case. Likewise the apparent air-bone gap could be artificially decreased by as much as 6 dB, for similar

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reasons. In other words, it is not sufficient that the instrument is within specification: it needs also to be individually calibrated to within ± 1 dB of the nominal values and maintained in calibration. It should be noted also that deviations from the absolute standard may arise even in well-equipped audiometric centres. This is particularly so for bone conduction, where the requirement that the mechanical coupler be equilibrated to a temperature of exactly 23°C is extremely difficult to ensure in practice; a deviation of 2°C is equivalent to a calibration error of about 1 dB.

Recently the reference zero for BC calibration (BS 2497, Part 4: 1972) has been replaced. The new standard, BS 6950: 1988, uses a different method of measurement and is based on more recent standardizing experiments. The new standard will typically yield BC thresholds that are about 3–4 dB less acute averaged over 1, 2 and 3 kHz as compared with the old standard, and about 5–8 dB less acute at 1 kHz in particular, depending on the date of manufacture of the mechanical coupler used for calibration. The evidence from both Robinson and Shipton (1982) and also from the National Study of Hearing is that the previous standard was in need of amendment. That helps to explain why, with audiometers calibrated to the older standard, it has been not uncommon to see material air-bone gaps in the region of 1 kHz in cases with no other evidence of conductive disorder. This has led to artificially reduced assessments of the amount of noise-induced hearing loss where a compensation scheme making (conditional) use of BC thresholds has been applied. In summary, instruments calibrated to the old BC standard tend to exaggerate air-bone gaps averaged over 1, 2 and 3 kHz by about 3–4 dB.

The BC calibration standard was based on BC thresholds measured with the non-test ear exposed to 35 dB of effective masking, and with the vibrator applied to the mastoid prominence on the side of the test ear. This ensured the prerequisite of strictly unilateral measurements for such standardization work, but inevitably introduced an element of central masking. Central masking effects have two consequences. They tend to increase the standard deviation of repeated BC thresholds, and thus inflate somewhat the measurement uncertainty compared with not-masked thresholds. They must also have influenced the BC standard reference level, such that if masking is not used in clinical testing this will introduce a bias towards an increased air-bone gap. This central masking effect amounts to some 3–5 dB (Shipton and Robinson, 1981). Furthermore, it is sometimes assumed that the same BC threshold is found whichever mastoid prominence the vibrator is applied to. However this is only approximately true and there is in fact a transcranial loss of several decibels. Testing should therefore be done with ipsilateral vibrator placement, as in the standardization experiments.

Occlusion effects

Occlusion of the external meatus of the test ear, e.g. by an earphone or earplug, enhances hearing by BC at frequencies up to 2 kHz. It is important therefore for tests in this frequency range that the test ear is not occluded in BC tests. The same rule applies to the non-test ear for any such BC tests carried out without masking, since the masking insert or earphone itself will produce an occlusion effect which may contribute to the apparent BC thresholds. However once contralateral masking noise is properly applied, it ensures that the non-test ear cannot influence the measured threshold.

Airborne radiation

Bone vibrators emit both mechanical vibration and airborne radiation. At frequencies above 2 kHz they may emit acoustic radiation that is more audible than the vibratory stimulation, and thus may produce artefactual BC thresholds. For tests at 4 kHz, the effect is large enough and frequent enough to require placement of an efficient earplug in the test ear. At 3 kHz , the effect is smaller and not found with all bone vibrators. For tests at 3 kHz using audiometric bone vibrators, it is therefore usual to omit the considerable practical inconvenience of plugging the test ear: this is acceptable provided it is recognized that in some cases this may produce a slight artefactual air-bone gap.

Background noise

Audiometry must always be carried out in an acoustical environment which is quiet enough to ensure that measurements within the range of interest are not significantly affected by the masking effect of ambient noise in the room. The requirements are more severe in BC testing than in AC testing since some advantage is gained by the noise reduction provided by wearing earphones. The actual limits of ambient noise acceptable for BC testing depend upon (a) the lowest hearing threshold level of interest (which, for a normal ear— or perhaps the better ear in a case of unilateral loss—could be as low as −10 dB HL), (b) the lowest audiometric frequency to be tested, and (c) the criterion of acceptable threshold shift that the ambient noise may cause. Scientifically derived noise limits have been recommended, e.g. by Berry (1973) and by Shipton and Robinson (1975), and adaptations of these have been incorporated in standards BS 6655: 1985 and ISO 8253–1: 1989. In the context of disability assessment based on the 1, 2 and 3 kHz frequencies only, appreciable relaxations of these specifications are admissible (D. W. Robinson, personal communication) and have recently been recommended by the British Association of Otolaryngologists in its 1990 annual newsletter to its members. Establishing conformity with the appropriate limiting values requires noise measuring equipment capable of 1/3-octave band analysis and having an internal 'noise floor' lower than the ambient noise levels to be measured.

Interpretation of results

Quite apart from the technical factors described above which limit the accuracy of audiometric measurements, there is an additional factor which has to be borne in mind in the case of bone conduction. The BC calibration standard is based on normal hearing, but it is known that obstructions of the middle-ear transmission path have an effect upon bone conduction, the so-called Carhart effect, as well as the more obvious elevation of

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AC threshold. The effect of this is that a conductive loss, if of appreciable magnitude, will give rise to a measured BC threshold that exaggerates the loss occurring at the cochlea. In other words, the non-compensable component is not given directly by the magnitude of the air-bone gap, but by some larger amount. Provided no other complication is present, the AC threshold is substantially raised, and the apparent air-bone gap (averaged over 1, 2 and 3 kHz) is more than about 15 dB, a gradually increasing figure of up to 15 dB should in principle be added to the air-bone gap to correct it for the Carhart effect. An overall uncertainty in air-bone gap (ABG) measurement of about ± 15 dB has also to be taken into account. The latter figure of 15 dB is arrived at by taking the upper 95% confidence limit for air-bone gaps in normal listeners (approx. 10 dB) and arbitrarily adding a further 5 dB to account for non-ideal test conditions, tolerances in calibration, and deviations from the median occlusion and airborne radiation characteristics.

It is considered that a reasonable compromise for determining the amount of non-compensable (conductive) loss in the ear in question is as follows:

Range of measured air-bone gap (dB)	Amount of conductive hearing loss (dB)
15 and below	Nil
15 to 30	(ABG–15 dB)
30 and over	ABG

ABG: Air-bone gap

Middle-ear disorders may occasionally give rise to an incidental element of sensorineural hearing loss as well. This seems to be a rare event, except in cases associated with such complications as suppurative labyrinthitis (Walby *et al.* 1983; Browning and Gatehouse, 1989). However, if there is unambiguous evidence of such secondary sensorineural involvement, the assessment of the non-compensable loss should in principle be still further increased. Quantitative estimation of this effect has not been satisfactorily established though, and no recommendations can be given here.

Conclusions

1. In assessment of auditory disability from the pure-tone audiogram, AC measurements should be used in preference to BC. This is due to the greater precision associated with AC threshold measurements, difficulties in interpretation of BC thresholds, and their unrealism (we do not normally hear by bone conduction). The exception is where there is a substantial element of conductive hearing loss, when the BC thresholds will have to be taken into account.
2. Definition of what is a substantial air-bone gap should be based on an average over the relevant frequencies, e.g. 1, 2 and 3 kHz, and not on single frequencies. This is because of the lesser measurement uncertainty associated with the average.
3. Taking account of all the possible sources of error, only an air-bone gap averaged over 1, 2 and 3 kHz greater than 15 dB can be regarded as significant, when measured with an audiometer whose BC output is calibrated to BS 6950: 1988. When an audiometer has been used that is calibrated to the earlier standard (BS 2497, Part 4: 1972) only an air-bone gap greater than 20 dB should be regarded as significant.
4. Audiometric data are only acceptable where the following conditions apply. (a) The audiometer complies with BS 5966: 1980 and has been calibrated to specified standards and periodically checked. (b) The audiometer is used in an appropriately quiet acoustic environment. (c) The tester follows an authoritatively recommended audiometric technique, e.g. that jointly recommended by the British Association of Otolaryngologists and the British Society of Audiology (Anon, 1981). (d) Any BC thresholds are measured with the vibrator placed on the mastoid process of the test ear. (e) Sufficient masking is used (i) to ensure that the non-test ear has made absolutely no contribution to hearing the BC signals, which requires an appropriate form of plateau-seeking masking procedure e.g. that recommended by the British Society of Audiology (Anon, 1986), and (ii) to include a masking level as close as possible to the test conditions under which the BC calibration standard was derived, i.e. with about 35 dB sensation level of masking noise in the non-test ear. An example of how condition (e) can be achieved without excessive test time is given in the Appendix.
5. In making BC measurements at any frequency up to and including 2 kHz, the test ear must not be occluded by an earphone or insert, in order to avoid enhancement of bone conduction due to the occlusion effect. For any BC measurements above 3 kHz, the test ear must be occluded by an efficient earplug, in order to prevent possible hearing of the signal by airborne acoustic radiation. At 3 kHz it is desirable to use an earplug, but acceptable not to do so—as discussed in the section above on airborne radiation.

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APPENDIX

Bone-Conduction Measurements in Medicolegal Clinics

The rules for when to use masking are much more strict for medicolegal work than those used for clinical diagnostic purposes. For accurate quantification of an air-bone gap, fully masked measurements of BC thresholds are needed in each ear and at each of the frequencies at which accurate quantification is required. Masking is needed even if the not-masked threshold is equal to or higher (less acute) than the AC threshold. The only exception is where the whole hearing loss on one side is known to be non-compensable, when there is no need for more than diagnostic BC measurements on that side.

The procedures described below have been designed for cases where accurate measurements of BC threshold are required at 1, 2 and 3 kHz for each ear. They could also be applied to any other frequencies requiring accurate quantification, except that for BC tests at and above 4 kHz the test ear must be plugged to prevent hearing of airborne radiation from the vibrator.

(1) Place the BC vibrator on the mastoid prominence of the ear which has the better AC threshold averaged over 1, 2 and 3 kHz.

(2) Measure the not-masked BC thresholds at 1, 2 and 3 kHz, with both ears unoccluded. Plot the result on a masking function chart such as that recommended by the British Society of Audiology (Anon, 1986). Use a separate chart for each frequency, and plot the not-masked threshold with a triangle symbol, placed beside the left-hand margin of the chart.

(3) Place the masking earphone on (or in, if it is of the insert type) the opposite (contralateral) ear but do not obstruct the test ear. Measure the thresholds (M) in the opposite (contralateral) ear for the narrow-band masking noises centred on the test tones of 1, 2 and 3 kHz.

(4) Remeasure each of the three BC thresholds with a masking noise level equal to (M+35) dB applied to the contralateral ear. Plot the result on the masking function chart according to the dial level of the masking noise, using a small filled circle as the symbol.

(5a) For each frequency, if the 35 dB-masked threshold is raised (less acute) by only 5 dB, unchanged or lowered (more acute), record the 35 dB-masked threshold level as the definitive threshold.

(5b) Otherwise (if it is raised by more than 5 dB), apply a full plateau-seeking masking procedure by remeasuring the threshold with such lower and higher levels of masking noise as may be needed to define the plateau level. Use the masking function chart to plot the results and to record definitive threshold.

(6) Move the BC vibrator to the mastoid prominence of the other ear, and repeat steps (2)–(5) for that ear.

Notes

(A) It is necessary to measure any negative air-bone gaps (BC less acute than AC) precisely, in order to calculate the average air-bone gap properly. This should be done for all three frequencies, even if after masking one or two of the three frequencies it becomes evident that on averaging across frequencies there would no longer be a positive air-bone gap (or a gap greater than some magnitude predefined as significant for purposes of compensation assessment). This is because the actual air-bone gap thus measured may later have to be considered in relation to air-bone gap measurements carried out elsewhere or at another time.

(B) Where the thresholds are thought to be unreliable, proceed as follows. Measure the not-masked BC thresholds only, at 1, 2 and 3 kHz on each side. If the subsequent cortical electric response audiometric tests show the AC thresholds to have been correct, masking of the BC tests may have to be carried out later.

(C) Occasionally, there will be too much hearing loss in the non-test ear, or too low an uncomfortable loudness level, to enable masking noise at 35 dB SL to be used. In such cases use a masking function chart to indicate the results for the masking levels actually used and draw conclusions on the most likely true BC threshold (x dB) according to the limited data available, simply recording it as 'at or over x dB' if that is as far as the conclusion can be drawn. If too little masking noise was used, such that a judgement could not be made, add 5 dB to the not-masked BC threshold (y dB) and record it as 'probably at or over (y +5) dB' to indicate the most likely lower (most acute) limit of the BC threshold. If a material element of cross-hearing appears to be unlikely, however, the estimated threshold can be recorded as 'probably (y + 5) dB'. This 5 dB addition makes the best statistical approximation to the central masking component embodied in the calibration standard.

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