The Journal of Laryngology and Otology
November 1993, Vol. **107**, pp. 985–989

When is a decibel not a decibel?: The application of decibel scales and calibration in clinical audiology

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Abstract
Decibel scales are a very important but potentially confusing subject for the clinician. Misunderstanding can, at worst, lead to inappropriate management which is detrimental to the patient. This paper sets out, from the viewpoint of an acoustician, the calibration and meaning of the various decibel scales in common use, shows how they are applied to the clinical setting, and explains their limitations.

Key words: Auditory perception; Calibration; Hearing

Introduction

The subject of decibels in otolaryngology and audiology is one that has confused and perplexed many a clinician. The different scales of decibels, be it dB(A), dB(HL), or dB(SPL), can leave one wondering why Alexander Bell is remembered so fondly if the decibel scale was his idea (Hassall and Zaveri, 1979)! However a reasonable understanding of the meaning of the various scales and the differences between them is essential for the clinician who has to make decisions that are based partially on audiometric results expressed in these various terms. The aim of this paper is to provide assistance in such understanding, especially in the area of sound-field measurements which have been a frequent source of confusion.

The purpose of the decibel scale – the dB

The decibel is a logarithmic unit that is used to express the relative magnitude of two quantities. If we want to compare quantities A and X in decibels we take the logarithm of the ratio A/X and then multiply by ten; this is expressed as 10 log (A/X) decibels. If we keep the quantity X fixed then we can express the magnitude of another number B in the same way i.e. 10 log (B/X) decibels. Comparing the two logarithmic measurements with respect to X (called the reference level) then allows us to compare the relative size of A and B. This is a useful technique for comparing a very large range of numbers as it compresses the range to a manageable size.

The measurement of sound power is an area where the ranges involved are extremely large and the decibel scale becomes useful. The acoustic power of a whisper is 10^{-9} W, whereas that of an aircraft is 50 000 W. This is obviously an unmanageable scale for practical use. Using a reference level of 10^{-12} W, these two figures then become 30 and 167 decibels respectively and we can say that the sound power of an aircraft is 137 dB greater than that of a whisper rather than saying it is 5×10^{13} times greater. Any reference value could be used to create a decibel scale but by universally agreeing on the reference level the decibel scale becomes very useful as all are then referring to the same absolute power.

This results in the dB SPL scale: i.e. the sound pressure level (SPL) expressed in decibels (Hassall and Zaveri, 1979). The compression of the scale of SPL allows a simple comparison of different quantities of acoustic energy but does lead to some confusing outcomes; for example, doubling the power of the source gives an increase of only three decibels.

The concept of A-weighting – the dB(A)

The loudness of a sound that a person perceives is not necessarily directly related to its power in dB SPL. This creates a need for a scale that reflects the subjective loudness of sounds, and this is what led to the development of the A-weighted version of the decibel scale, the dB(A), (Hassall and Zaveri, 1979).

The human perception of loudness depends on the intensity of a sound at the eardrum. This intensity is obviously related to the sound level that exists in the environment outside the ear but it is also affected by other factors. If we measured the sound level in a room using a microphone as shown in Figure 1 and then put a person in the room and measured the sound level at their eardrum the two levels would be different. Firstly, the presence of a head and torso would cause reflections and diffractions of the sound wave which affects the intensity of the sound at the entrance to the ear canal so the level at point *a* in Figure 2 is different from that measured in Figure 1. Then, in passing down the ear canal, there are resonance effects which affect the intensity of the sound arriving at the eardrum; so, in Figure 2, the sound level at point *b* is different to that at point *a*. We call these effects the *transformation characteristics* – the character of the transformation of the sound in arriving at the eardrum (Shaw, 1975). An

Accepted for publication: 26 May 1993.

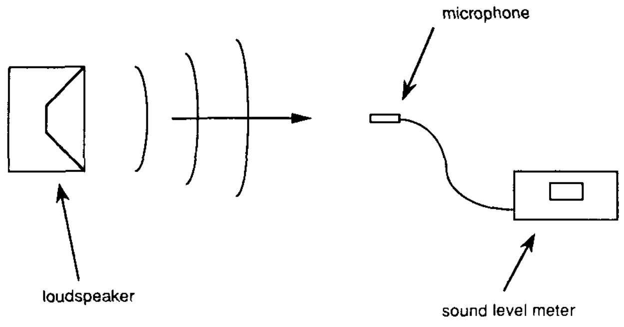

FIG. 1
Measuring the sound pressure level in an empty sound field.

example of the transformation characteristics from an empty sound field (i.e. like Figure 1), to a subject's eardrum are shown in Figure 3 – this graph shows the difference between the sound level measured in Figure 1 to that at point *b* in Figure 2. We can see that the transformation characteristics vary significantly with frequency.

Therefore the sound level that exists at the eardrum is different from that measured in an empty sound field and this difference varies with frequency. These transformation characteristics obviously affect the perceived loudness of a sound and so must be taken into account in creating a scale that reflects perceived loudness.

In addition to the factors affecting the sound level at the eardrum, once a sound arrives there the ear then has different sensitivities to different frequencies (Killion, 1978). The sound pressure level at the eardrum corresponding to the threshold of hearing is called the minimum audible pressure (MAP). A plot of the MAP against frequency is shown in Figure 4. It can be seen that the SPL at the eardrum corresponding to threshold varies greatly with frequency. This variation in sensitivity means that, for example, 20 dB SPL of a 1 kHz tone at the eardrum will be perceived as being a different loudness to 20 dB SPL of a 4 kHz tone.

Hence, because of the effect of the transformation characteristics and the variation in MAP, the dB SPL scale does not accurately reflect the perceived loudness of sounds of different frequency. To give an example, while a 1 kHz tone of 33 dB SPL is perceived as twice as loud as a 1 kHz tone of 30 dB SPL, it may be louder or quieter than a 33 dB SPL signal of a different frequency.

The A-weighted scale takes into account the difference in perceived loudness for different frequencies. One kHz has been chosen as a reference frequency and other frequencies were weighted so that their perceived loudness was the same as a 1 kHz tone (Hassall and Zaveri, 1979; ISO 226, 1987). In other words the transformation characteristics and the variation in sensitivity for different frequencies were taken into account so that a sound of X dB(A) at any frequency results in the same perceived loudness. For example a 30 dB(A) 1 kHz tone will be perceived as being the same loudness as a 30 dB(A) 4 kHz tone. In this example the absolute SPL's present at the eardrum may be very different, but the amount by which they exceed the respective MAP will be the same, so giving the same sensation of loudness. The dB(A) scale then allows measurement of hearing in a way that is practically useful by allowing comparison of the loudness of sounds of different frequencies.

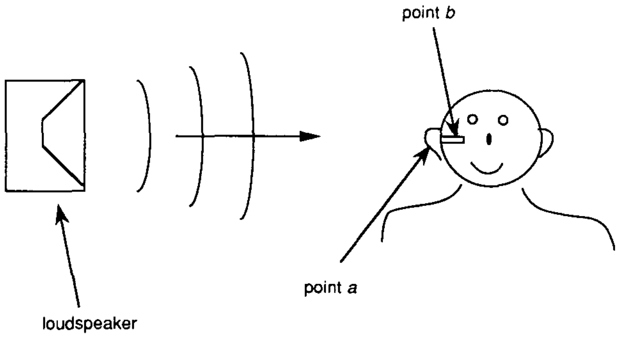

FIG. 2
Measurement points when a listener is placed in a sound field.

The limitations of A-weighting – the dB(A) problems

When we consider clinical measurements of hearing the dB(A) scale has two main limitations. Firstly, the A-weighted scale was developed for a subject sitting in a sound field that involves a wave of sound coming from a source directly in front of them and with no reflections, technically this is called a frontally incident, plane, progressive wave and is only achieved in an anechoic chamber (ASHA, 1991). If the presentation of sound is changed, for example if the source is to one side, or if reflections are present so causing the sound to arrive from several angles, then the reflections and diffractions caused by a human listener change and the sound intensity at the eardrum is altered. In other words the transformation characteristics that the dB(A) scale was accounting for have changed (ISO 226, 1987). The extreme case is that of wearing headphones where the effects of the head and torso are obviously completely bypassed. A graph of the transformation characteristics for a headphone, for a free-field and for a diffuse field are given in Figure 5 – if we compare these different curves we can see the large variation between different methods of sound presentation. For example comparing a free-field to a diffuse field, at 4 kHz the sound pressure at the eardrum is 5 dB louder in the diffuse field. Using the dB(A) scale in a diffuse field would result in measurements being 5 dB too low at this frequency.

Therefore, although the absolute sensitivity of the ear has not changed, a difference in the presentation of the

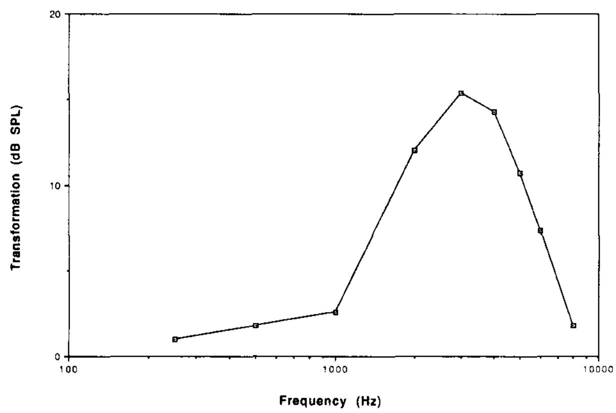

FIG. 3
Transformation from the free-field to the eardrum. Data from Shaw and Vaillancourt (1985).

https://doi.org/10.1017/S002221510012506X Published online by Cambridge University Press

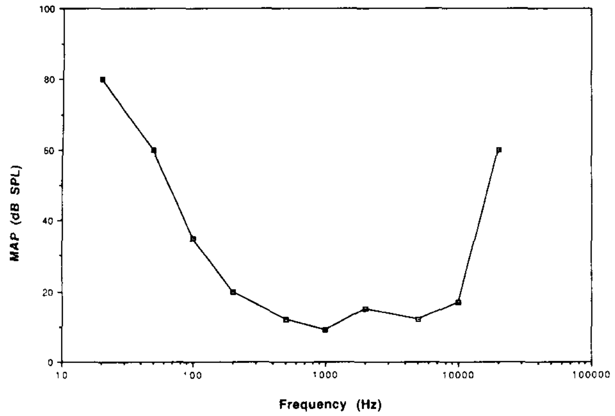

FIG. 4

Minimum Audible Pressure (MAP). Data from Killion (1978).

sound, changes the transformation characteristics that the A-weighting was trying to correct for. As a result the dB(A) scale is no longer applicable to situations that vary greatly from a frontally incident, plane, progressive wave and so is unsuitable for many audiological situations (ISO 226, 1987). It is most applicable to sound-field testing but as clinical test rooms rarely approach anechoic it has to be recognized that some errors may be incurred in using this scale.

The second limitation of the dB(A) scale is the arbitrary choice of zero, which does not relate to the threshold of hearing. The weightings for perceived loudness were made with respect to a 1 kHz tone at 40 dB SPL. This does not give a SPL at the eardrum 40 dB greater than the minimum audible pressure and so 40 B(A) is not 40 dB above threshold. The result is that 0 dB(A) reflects the perceived loudness of a 1 kHz tone at 0 dB SPL, rather than the threshold of hearing which is approximately 5 dB higher. In practice this means that measurements in dB(A) will consistently over estimate hearing loss.[1]

Use of the dB(A) scale in clinical measurements is therefore flawed in two areas: it is expressly designed for use in a true free-field which is rarely encountered in clinical testing, and its arbitrary choice of 40 dB SPL as reference results in the dB(A) scale not measuring hearing relative to threshold.

Decibels and hearing level – the dB HL

The dB HL scale is a general term for a scale that reflects the perceived loudness of sounds at different frequencies and measures them with respect to the threshold of hearing. To develop a hearing level scale means accounting for the variation in sensitivity at the eardrum and the transformation characteristics present, and having a zero that corresponds to the threshold of hearing. The hearing level scale is applied to any situation where these factors are taken into account such that the perceived loudness of sounds is measured. The transformation characteristics vary depending on how the sound is presented and so different correction factors must be found for each method of presentation. If we knew the transformation characteristics, say for an earphone (i.e. the difference between the SPL next to the earphone and that at the eardrum for each frequency), then we could add them to the MAP to find the output level that should correspond to threshold. It is quite difficult to predict what the transformation characteristics will be however and so rather than adopt such a theoretical approach an experimental one is used instead.

If we take the case of earphone presentation the hearing level scale is developed by finding the threshold of a large number of otologically normal subjects. If the dial reading on the audiometer for the average threshold at each frequency is labelled 0 dB HL the audiometer is then calibrated to measure hearing level. This sets the output levels at 0 dB HL for what has just been found to correspond to threshold. This is known as a biological calibration. The transformation characteristics have not been quantified but they have been taken into account as they will have affected the SPL at the eardrum as the thresholds were found.

It is extremely cumbersome to go through this process each time an audiometer is to be calibrated so the output levels corresponding to threshold were recorded in such a way that the subjects do not have to be retested. These levels were recorded by placing the earphone on a coupler (a small cavity with a microphone in it) and measuring the SPL created in the coupler for the audiometer set at 0 dB HL i.e. at the output levels corresponding to threshold (ISO 389, 1985). Therefore to calibrate another audiometer, rather than performing a biological calibration, the earphone is placed on a coupler and the output levels of the audiometer varied until they are the same as the recorded values. This ensures that the output levels at 0 dB HL are the same as those originally found to correspond to the threshold of hearing. The levels measured in the coupler are not of course the same as those present next to the eardrum as the volume and impedance of the coupler are very different to that of an ear; rather these levels just act as a reference point to obtain the same output level as originally found.

It must be noted that these values will be different if the earphone (including the loudspeaker and the cushion) or the coupler is different from those used originally, as a different SPL will be generated in the coupler (Shaw, 1966). That is why, when calibrating an audiometer, it is impor-

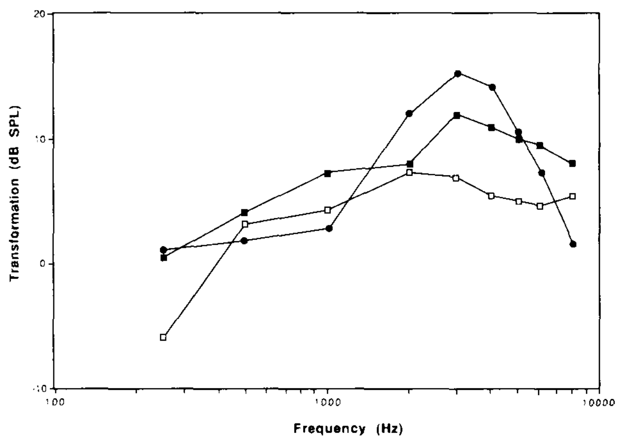

FIG. 5

Transformation data for different sound presentations. Data from Shaw (1966), Shaw and Vaillancourt (1985), and Kuhn and Guernsey (1983). □, earphone; ◆, free-field; ■, diffuse field.

[1]The exception to this is at 3 to 4 kHz where the smoothing effect of A-weighted filters result in an underestimate.

tant to ensure that the values used are for the earphone and cushion in question. The values that correspond to threshold are called *reference equivalent threshold sound pressure levels* (RETSPL's). The reference levels for earphone and bone vibrator testing have been agreed upon internationally and are given in ISO 389 (1985) and ISO 7566 (1987) respectively.

Calibration in sound fields – the dB HL question

The method (outlined above) of finding the output level that corresponds to threshold and then recording it in some way is the basis of all audiometric calibration. When applied to sound-field audiometry the issue is essentially the same but can lead to various problems. Ideally the threshold of a large number of otologically normal subjects would be found and the output levels recorded – the method of recording the output level is that a sound level meter is placed, with the microphone, at the centre point of the subject's head. This would take into account the transformation characteristics present and allow recalibration using the reference levels in the same way as for headphone calibration. However the transformation characteristics depend on the nature of the sound field present and this is affected by a number of factors which vary between clinics. The orientation of the speaker, the characteristics of the test signal, the distance between the speaker and the subject, and the size and absorptivity of the test room all affect the nature of the sound field generated (ASHA, 1991; Beynon, 1992). The inference is that an individual set of reference values have to be found for each individual test set-up, but this also contains its own problems.[2] This method of finding individual reference levels for each test set-up is used in calibrating any system where national or international standards have not been agreed upon e.g. evoked response by audiometric equipment. The strict notation for equipment calibrated in this way is dB nHL (normal hearing level) rather than dB HL.

Attempts have been made to find a set of reference values for sound-field testing that are suitable for a typical audiometric test room; these are given in Table I. The best of these are those suggested by Walker *et al.* (1984). These values have been evaluated by comparing sound-field results, after calibration with these values, to earphone measurements (Cox and McCormick, 1987). These comparisons showed that the mean error was very small i.e. on average the values are very accurate, but the standard deviation was 5.2 dB. This means that to include 95 per cent of the possible error in using these reference figures a range of ± 10 dB has to be applied to sound-field results. Therefore if audiologists use these figures, as they are beginning to do, clinicians need to be aware of the possible errors involved. The threshold at any one frequency can be 10 dB higher or lower than that found due to these errors in calibration. It is extremely unlikely though that errors will be consistently present across the frequency range; therefore on average the audiogram should give an accurate estimation of hearing level. This should hopefully lead to clinicians not putting too much store by the threshold at a single frequency.

It is also worth noting that retesting will not help in eliminating these errors as they arise from the calibration of the equipment rather than from variation in the test itself (e.g. subject movement, concentration, etc.). Retesting to help eliminate these other sources of error is entirely justified.

At present a great variety of methods are used in reporting sound-field results. This can result in sound-field thresholds that are calibrated in dB(A), or not calibrated at all, being marked on an audiogram and compared with earphone measures that are in dB HL. This is at best confusing and at worst can mislead clinicians into inappropriate management. As was mentioned earlier the dB(A) scale is not entirely suitable for sound-field testing, but it has gained great popularity out of the need to have a common scale. When dB(A) scales are used two points need to be remembered. Firstly, comparison with other measurements in dB HL such as aided/unaided comparisons may involve substantial errors. This is treating the dB (A) scale as if it is a dB HL scale calibrated for the individual sound field in question. Therefore measurements in dB(A) marked on audiograms are very misleading and should be clearly marked as being on a different scale to the rest of the graph – a better policy would be to never report dB(A) results in this way. Secondly, comparison of results in dB(A) that have been obtained in different test set-ups can lead to confusion. Differences may be present that are simply due to the different sound-field characteristics present rather than as a result of any change in hearing sensitivity. This point is also true of using Walker *et al.* (1984)'s suggested levels and will never be overcome unless all sound-field systems are individually calibrated in dB HL.

The dB(A) scale is a useful one, especially for establishing screening levels, and audiological results will no doubt continue to be reported using it, but the clinician must remember that it is not the same as dB HL and treating it as such can lead to wrong conclusions about the hearing of a patient. Dialogue is clearly necessary between otolaryngologists and audiologists as to which method is to be used and how results should be best reported.

The issue of sensation level – the dB SL

Another scale sometimes used in tinnitus matching and

TABLE I

MONAURAL REFERENCE EQUIVALENT THRESHOLD SOUND PRESSURE LEVELS (RETSPL'S) FOR DIFFERENT ANGLES OF INCIDENCE (FROM DIFFERENT SOURCES)

Angle	Source	Frequency 0.25	0.5	1	2	4	6	8
0 degree								
	M, D & B[a]	15.0	11.5	8.0	2.5	2.5	–	–
	W, D & B	16.0	9.5	5.5	2.5	1.5	7.5	13.0
	S	15.0	11.0	7.0	3.0	−3.0	6.0	–
45 degrees	M, D & B	20.0	8.0	4.0	4.0	−4.5	3.5	–
90 degrees	M, D & B[a]	15.0	6.5	2.5	5.0	−2.0	–	–
	W, D & B	16.0	7.5	3.5	4.0	1.0	1.5	9.0

Key: M, D & B: Morgan *et al.* (1979); M, D & B[a]: Morgan *et al.* (1979) based on data from Stream and Dirks (1974); W, D & B: Walker *et al.* (1984); S: Skinner (1988).

[2]The main problem is that of background noise which has to be extremely low before thresholds can be found in a sound field. Ear plugs can be used to artificially raise the hearing level by a known amount but quantifying this amount accurately is difficult. Hearing impaired subjects can be used and the sound-field results corrected by the hearing loss which is found by earphone testing. The main problem with this technique is deciding how two monaural thresholds from earphone testing combine to give a binaural threshold in sound-field testing.

masking is that of sensation level (dB SL). This refers to the loudness that a listener experiences – their *sensation* of loudness. This is therefore dependent on what their threshold is at the frequency in question. A person with normal thresholds listening to a tone at 40 dB HL will experience a loudness of 40 dB SL; if their threshold is 30 dB HL however then they experience a loudness of approximately 10 dB SL. This seemingly straightforward concept is complicated by the presence of recruitment. In the given example any abnormal growth in loudness will result in the sensation level being greater than 10 dB. Therefore if a patient is recruiting then subtracting their threshold from the stimulus intensity they will underestimate the sensation level. Also differences in measurement procedure will lead to different results when attempting to estimate sensation level. The result is that sensation level is a useful concept but is hard to measure accurately and consistently in practice.

Recommendations

(1) The dB SPL scale should be recognized as a measure of absolute sound pressure level and so should not be used in reporting any measurements relating to hearing level.

(2) Where the dB(A) scale is used results should not be compared with results in dB HL.

(3) Efforts should be made to calibrate sound fields in dB HL so as to provide a common scale that allows direct comparison of results.

(4) Clinicians should be aware of the potential errors involved in sound-field measurements and discuss with audiologists the reliability and reporting of such measurements.

(5) Measurements of sensation level should be taken cautiously (because of the unknown effects of recruitment). Discussion is needed between the involved parties as to what measurement protocol is used and how these results are reported.

We cannot escape the decibel scale in the world of hearing much as many of us would like to. Hopefully this paper has helped make clear some of the intricacies and subtleties involved so that we can have more confidence in knowing when a decibel really is a decibel.

Acknowledgements

I would like to thank David Baguley, Dr J. D. E. Beynon and Posy Marriage for their constructive comments and help in writing this paper.

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