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A review of the relative technical and practical merits of the IEC reference coupler and artificial ear and their future role in pure-tone audiometry

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A REVIEW OF THE RELATIVE TECHNICAL AND PRACTICAL MERITS OF THE IEC REFERENCE COUPLER AND ARTIFICIAL EAR AND THEIR FUTURE ROLE IN PURE-TONE AUDIOMETRY

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ABSTRACT

Pure-tone air-conduction audiometry has become the foundation of hearing assessment. The audiometer, and in particular the earphones used with it, need to be calibrated to ensure measurement traceability. Hearing threshold measurements are then referred to established reference levels to then judge if any hearing loss is present. Ear simulators are used in this process to provide an objective means of determining the sound pressure level presented during a test. At present ISO 389-1 requires the IEC reference coupler to be used for the calibration of a limited number of supra aural earphone configurations and the IEC artificial ear to be used for all other types. In this part of a collaborative project with ISVR, this report suggests that the artificial ear be used universally and shows that users of these devices have responded positively to this recommendation. It thus goes on to propose to ISO that the sole use of the artificial ear and its RETSPL values be the basis for a revision of ISO 389-1.

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1. INTRODUCTION

Pure-tone air-conduction audiometry has become the foundation of hearing assessment methodology since 1879 and the first commercially produced device for measuring hearing - the Hughes audiometer[1]. Modern practices enable the hearing threshold level of a subject to be determined relative to the threshold level for normal hearing, and therefore provide diagnostic information on the state of the hearing of that subject.

The basis of the test is that the subject has an earphone fitted to one ear. The earphone is driven by an audiometer to produce sound pressure in the ear under test. The subject is then able to control the level of the sound and adjusts it to a level that is just discernable. The audiometer records this level, which then establishes the hearing threshold of the given ear. The audiometer must therefore be calibrated to ensure traceability for this measurement. Part of the calibration process involves adjusting the electrical drive level supplied to the particular earphone connected to it, so that the acoustic output of the earphone is of the required level. The acoustic output is specified in terms of the sound pressure level (SPL) produced in a mechanical device used to simulate the human ear and containing a microphone to measure the SPL. Such a device is known generically as an ear simulator.

The hearing threshold level of the subject only provides half of the information required for the diagnosis of any hearing loss. The measured threshold needs to be compared with some reference level indicative of normal hearing. The reference equivalent threshold sound pressure level or RETSPL establishes this reference level. It has been determined by measuring the hearing threshold levels of a large group of ‘otologically normal’ young adults and establishing the average value of these measurements, with each hearing threshold being established in terms of the SPL developed in an ear simulator. This is referred to as the equivalent threshold.

The hearing level of a subject is then defined as the difference (in decibels) between the measured hearing threshold level of the subject and the RETSPL. This type of measurement is built-in to most audiometers, which report the hearing level as a function of frequency in the form of an audiogram.

Thus, the role of the ear simulator in hearing measurement is two-fold. It has been used initially to establish the reference level, the RETSPL, and is also used for the routine calibration of audiometers.

Standardisation of RETSPL data is key to the consistent measurement of hearing threshold level which in turn reflects on the accuracy of medical diagnosis of hearing loss, the educational placement of children and the auditory rehabilitation of adults.

At present two types of ear simulator exist for the calibration of audiometers fitted with supra aural earphones (earphones designed to rest on the pinna, and the most commonly used type in audiometry). These devices are the IEC 60318-3 reference coupler and the IEC 60318-1 artificial ear†. Associated RETSPL values for each of the ear simulators, for use with specific or limited earphone types, are specified in ISO 389-1[2]. Unfortunately the earphone types that can be used with each ear simulator are mutually exclusive, so every calibration laboratory needs to maintain examples of both in order the cover the full range of earphones found in use. This adds cost and, in certain circumstances, leads to ambiguity over which ear simulator should be used. It has long been suggested that a single type of ear simulator for all types of earphone might improve this situation. Furthermore, if this ear simulator were able to offer a good simulation of the human ear, a single, universal set of RETSPL values is all that would be required.

† In this report these devices will be referred to by the names *reference coupler* and *artificial ear* respectively, but omitting the IEC reference numbers for brevity. Other devices will be referred to by their specific type and name or generically by the term *ear simulator*.

2. HISTORICAL DEVELOPMENT OF THE EAR SIMULATORS AND STANDARDISATION

The specification of the reference coupler, in terms of the basic design and key dimensions, is given in IEC 60318-3[3]. Work began on preparing this standard in 1962 after a need was identified for a device that could load an audiometric earphone with a well-defined acoustic impedance. It was recognised at that time that the SPL developed by an earphone in the coupler was not generally the same as that in a real ear, and that different RETSPLs were required depending on the earphone type. However the standard was developed to address a pressing need for the performance of audiometers to be specified and to enable the calibration of the associated earphones. The NBS 9-A coupler specified by the American National Standards Institute (ANSI) is very similar to the IEC reference coupler.

The reference coupler consists essentially of a metal cylindrical cavity with a nominal effective volume of 5.78 ± 0.08 cm^3, where the base of the cavity is formed by a measurement microphone for the determination of the sound pressure. The standard specifies a one-inch microphone fitted with an adapter that does not obstruct its diaphragm, in place of its normal slotted protection grid. This microphone configuration is specified in IEC 61094-1[4] and is referred to as a IEC type LS1 configuration. The angled face of the coupler where the earphone is applied is specified so that an earphone can rest and seal on the upper edge of the coupler. The coupling force required to seal an earphone to the coupler is specified by the standard as a force of 4 N to 5 N, in addition to the weight of the earphone itself.

As the instrumentation and techniques to measure acoustic impedance of the real ears developed, and normative data became available, the IEC were able to prepare specifications for an artificial ear (IEC 60318-1[5]), which effectively simulated the average human ear over a wide frequency range. Practical versions of these devices were produced, initially as prototypes or research tools, but later as commercial products. Using these devices it was found that the relative sensitivities of a number of earphone types in the frequency range 80 Hz to 8 kHz, gave closer agreement with subjective results than could be obtained with the reference coupler. Thus using a device that provided a better approximation to the acoustical impedance of a real ear appeared to give substantially improved results.

The design of the artificial ear is more complicated than the reference coupler. It consists of three acoustically coupled cavities and a half-inch measurement microphone (this time fitted with the usual protection grid), denoted IEC type WS2. Two of the cavities are coupled to the third by means of an annular slit and four narrow tubes respectively. The combined acoustical impedance of these elements and volumes are designed to approximate to that of an average human ear. As with the reference coupler, the face where the earphone is applied is designed to mate with the earphone with an applied coupling force of between 4 N and 5 N, in addition to the weight of the earphone. The IEC specification standard for the artificial ear was first published in 1970.

The American Standards Association (ASA), a forerunner of ANSI, first published the normal threshold of hearing by monaural earphone listening in 1951[6]. The first British Standard, BS 2497[7], followed 3 years later. It is interesting to note that ASA reference threshold values were some 10 dB higher than those published in the British standard. The aim of these standards was to promote consistency in the calibration of pure-tone audiometers, by establishing a standard reference zero for the scale of hearing loss. The values given in the British Standard were based on two studies in the UK where tests were made on over 1200 ears of otologically normal subjects aged between 18 and 25 years. An International recommendation (rather than a Standard) was issued by the International Organisation for Standardisation (ISO) in 1964 as ISO/R 389[8]. This gave the hearing threshold data in the form RETSPLs suitable for direct application to the calibration of audiometers, derived from data provided by various standardising laboratories, determined between 1950 and 1961. The RETSPLs were determined for various standard earphone types, measured on a range of ear simulators of stated (but not necessarily standardised) type. Further combinations of earphone and ear simulator were added to the standard in 1970. The document was given the status of a standard in 1975 following a change of policy in ISO. Further revisions during the 1980s and 1990s incorporated data for the artificial ear, additional frequencies, the removal of (by then) obsolete combinations of earphones and cushions, clarification on the equivalence of certain cushion types and some updating of definitions. Significantly, the RETSPLs for the artificial ear were not re-determined from new subjective data, but transferred, through a series of earphone measurements, from the reference coupler data. ISO 389 was formally adopted as a British standard in 1997, although the content of BS 2497 had been aligned with ISO 389 long before this. By 1998, hearing threshold standards had expanded into a series, with the original ISO 389 becoming ISO 389-1, and this remains as the current situation.

Both IEC and ISO have policies of re-visiting standards every 7 years or so. This enables their relevance and accuracy to be reviewed, as well as any changes in measurement practice or technological improvements to be added. The standard for the artificial ear is currently under revision and is expected to include a measurement method and tolerances for the acoustical impedance, including information on the measurement uncertainty. Its scope is also being expanded to cover circumaural earphones with the use of a suitable adapter (currently specified in IEC 60318-2[9]). This also enables the frequency range to be extended to 16 kHz, although the specification above 8 kHz will not be based on a realistic acoustical impedance. IEC 60318-3 is due for revision in the next 2 years. It is likely to include measurement uncertainties and a review of tolerances to take account of these.

Revision of ISO 389-1 is always a difficult task to contemplate since the consequences for existing and future hearing loss compensation claims are far-reaching. However ISO appointed a working group to this task and they are considering how best to review and update this standard.

3. REVIEW OF LITERATURE HIGHLIGHTING ISSUES WITH THE STANDARDS FOR HEARING THRESHOLD

The development of standards for hearing thresholds have already been outlined in the previous section. In 1968, Weissler[10] describes the amalgamation process that was used to bring all the data together into an international standard reference zero for audiometers. From his work it is evident that substantial error could exist and that these could have been perpetuated in subsequent revisions of ISO 389-1.

As early as 1965 Riley, Sterner, Fassett and Sutton[11] expressed dissatisfaction with the use of subjectively determined norms and they suggested that;

> "*audiometers be calibrated and hearing thresholds be recorded in terms of actual sound pressure level . . . this simple physical basis avoiding the inevitable uncertainties of a calibration based on a physiologic normal*"

A number of studies have looked at the performance of supra aural earphones measured on various types of ear simulator. A large proportion of the earphones used in these studies and used widely in audiometry, are manufactured by the Telephonics company. For brevity they will be referred to in this report (as they are in practice) simply by their TDH-prefixed model numbers.

Rudmose (1964)[12] discussed problems encountered when calibrating TDH-39 earphones with the NBS 9A coupler (equivalent to the IEC reference coupler) and the ASA type 1 coupler. This paper also highlighted a strong peak in its frequency response characteristic of the TDH-39 around 6 kHz and the fact that the earphone did not exhibit this same characteristic when coupled to the human ear. Howard (1968)[13] compared the frequency response characteristics of TDH-39 and TDH-49 earphones measured using the same two types of US-specified coupler with the pressure response produced in the human ear. For the TDH-39 earphone, the causes of the dip at 2 kHz and the peaks at 4 kHz and around 5.5 kHz were explained, the peak around 5.5 kHz being caused by an interaction between the coupler and the earphone. This is likely to be the same behaviour observed by Rudmose. Howard also discussed how this information was used to design the TDH-49 with greater damping, resulting in these earphones having a flatter and smoother frequency response to higher frequencies than TDH-39 earphones.

Robinson (1978)[14] collated the frequency response characteristics of a number of TDH-39 earphones in terms of their transfer SPL values - the difference between the SPL generated by an earphone on the reference coupler and on the artificial ear. Along with data for several other earphones types, most of which have now become obsolete. These data were used to enable RETSPLs to be calculated for the artificial ear, based on the data for the reference coupler. In his report, Robinson noted considerable intra-type variability at 6 kHz for the TDH-39. A further study to determine the normal threshold of hearing by Robinson, Shipton and Hinchcliffe (1979)[15] also measured transfer SPL values for a group of TDH-39 earphones and again found the data to be particularly variable at 6 kHz. In 1981, based on their findings, Robinson et al.[16] proposed corrections to ISO 389-1 (table 1) of 2.5 dB at 500 Hz and of 4 dB at 6 kHz.

Following this and other studies, RETSPL values for the artificial ear were published in ISO 389 in 1985. It is specifically stated that one set of RETSPLs in the standard applied only to a TDH-39 earphone with MX 41/AR cushion or a Beyer DT48 earphone with its flat cushion, calibrated on an reference coupler. This implied that if a TDH-39 earphone was fitted with the new style Model 51 cushion it should be calibrated using an artificial ear together with the separately specified RETSPLs for that device. However this has been the cause of much confusion amongst those responsible for audiometer calibration.

Dowson, McNeill and Torr (1991)[17] carried out an investigation into the equivalence of the MX 41/AR and Model 51 cushions at NPL and concluded that the cushion types can be taken as identical when fitted to TDH-39 earphones mounted on an reference coupler, except at 6 kHz where differences in earphone sensitivity of up to 2.8 dB were observed. However this investigation created a new complication by indicating that the differences at 6 kHz appeared to depend on whether the earphone was metal or plastic cased. These results were consistent with those of Michael and Bienvenue (1980)[18] except at 2 kHz where the latter authors found a difference of around 1 dB between the two earphone cushion types. ISO decided to revise the standard and clarify any ambiguity by defining the cushions as equivalent in ISO 389:1991[30]. It stated that the reference coupler should only be used with Beyer DT48 earphones with flat cushions and with TDH-39 earphones fitted either with MX 41/AR cushions or with the newer style one-piece Model 51 (P/N 510C017-1) cushions, when the RETSPLs given in Table 1 should be used. The artificial ear and RETSPLs given in Table 2 should be used for any other combination within specified limits. Although the MX 41/AR and Model 51 cushions are stated as equivalent, no mention is made of the equivalence or otherwise of metal and plastic cased earphones.

The appearance of plastic cased TDH-39 earphones was simply a result of manufacturing changes, but are now designated as TDH-39P to distinguish them from the earlier metal cased versions (though early plastic examples may not have been referred to in this way). Since many of the early studies on hearing threshold pre-date the introduction of these plastic cased earphones, the data they yielded is based only on metal cased examples.

Canning (1991)[19] measured transfer SPLs for TDH-39 and TDH-39P earphones and found a difference at 6 kHz of almost 10 dB, casting doubt as to whether the earphones used are truly equivalent. However the TDH-39 is a very popular model of earphone and a large proportion of the devices in circulation are plastic cased versions. Canning's findings cast doubt over whether the reference coupler and the associated RETSPLs are suitable for the calibration of THD-39P earphones. The findings also raise questions about the assumed similarity between the TDH-49 and the newer plastic cased TDH-49P earphones.

Since the 1990s various determinations of threshold level have been made. Burén et al. (1992)[20] reported deviations from ISO 389-1 as large as 7.5 dB at 125 Hz and 8 kHz, 5 dB at 250 Hz and 6 kHz, and smaller but significant deviations at the other audiometric frequencies, as a result of a study using 69 subjects in the age range of 18-22 years. The test protocol used for this study anticipated in many respects those to be recommended some 4 years later[28] but interestingly the earphones used (TDH-39) were calibrated using the artificial ear and RETSPL values from Table 2 of ISO 389-1 which explains why the characteristic 6 kHz notch is missing from their data.

Sherwood, McNeill and Torr (1995)[21] objectively quantify differences between metal and plastic cased TDH-39 and TDH 49 earphones at NPL. One resulting comment was on the unsatisfactory nature of the need for two standardised devices and two associated sets of RETSPLs. They concluded that a move away from the use of TDH-39 and TDH-39P earphones for air-conduction audiometry would both avoid the problem of differences in performances and facilitate the adoption of the artificial ear as a universal calibration device for supra-aural earphones. This is essentially the conclusion drawn by Delany[22] in 1967 but thirty seven years on the issue remains unresolved. Using the NPL earphones from the 1995 objective study, Qasem (1996)[23] carried out a subjective comparison of hearing threshold levels and also came to the conclusion that the artificial ear and associated RETSPLs should be adopted for the calibration of all supra aural earphone types, but this time on the basis of subjective measurement considerations. This view is supported by a number of further studies [23,26,27,29].

From the UK National Study of Hearing, Lutman and Davis (1994)[24] reported that the median pure-tone hearing threshold levels for otologically normal young adults were nearer 5 dB than zero in the frequency range from 500 Hz to 4 kHz, casting more doubt on the validity of ISO 389-1. The differences could be due to the modernisation of instrumentation and measurement practices, or reflect a real change in the hearing of the population. However both represent arguments for re-establishing the reference hearing threshold level if this is to reflect the expected hearing threshold of an adult with normal hearing.

Documents submitted to ISO TC43 WG1 by Smith (1996)[25], (1997)[26] and (1999)[27] presented results of further hearing threshold measurements showing significant deviations from ISO 389-1 values at all frequencies. One of these reports[25] also presents arguments for the calibration of all earphones using the artificial ear. Other recommendations on the preferred test conditions (see Preferred Test Conditions for Determining Hearing Thresholds for Standardization [28]) were also made.

The data from Smith, Davis, Ferguson, Lutman (2000)[29] strongly suggest that ISO 389-1 (1991)[30] for air-conduction audiometry (as well as ISO 389-3 (1994)[31] for bone-conduction audiometry) is in need of revision. They recommended that the revision should specify a single device for the calibration of earphones, and that this should be the artificial ear. They also recommended that a change be made to the

RETSPL values published in ISO 389-1 so that they more accurately reflect hearing in otologically normal young adults.

Martin (1997)[32] assessed the requirements for standardisation in audiometry and Hart (2000)[33] the practical use of ear simulators. Both reviewed the issues related to specification standards and highlighted problems with the reference coupler and ISO 389-1, and the need for a critical review of the standards. Hart went further in suggesting that ultimately a fundamental change is needed in the instrumentation used to measure hearing, particularly regarding the ear simulators used.

There are also discrepancies between the American Standard ANSI S3.6-1996[34] and the International Standard ISO 389-1 (1998). Both standards quote similar RETSPL values for the TDH-39 measured using the reference coupler. A small difference of 0.5 dB exists at 750 Hz. However the ANSI standard also presents reference values for TDH-49 and TDH-50 earphones measured using the reference coupler, a combination that ISO 389-1 does not allow.

4. OUTLINE OF PROJECT

The previous section has shown that there is a large body of evidence to suggest that a change is required in the basis for hearing measurement, in two respects. First whether the ear simulators and associated RETSPLs needed for the calibration of audiometers can be rationalised; and second, whether the RETSPLs themselves should be revised based on the latest data available.

To try and answer the first question, a collaborative project between NPL and the Institute of Sound and Vibration Research (ISVR) has been undertaken with these objectives to:

- review existing literature for evidence of the need to maintain both the reference coupler and artificial ear; to examine the relative technical merits of each device; and to consider whether one or other could be adopted universally,
- consider the implications of the recommendations arising from above, and to consult the UK users on their attitudes to these,
- make appropriate recommendations to ISO regarding the revision of ISO 389-1, based on the findings and attitudes of UK users.

The first objective was undertaken by ISVR and reported separately[35]. The main conclusions were that;

- while the THD-39 earphone was found to still perform well, there are no well-founded technical arguments for why it must continue to be calibrated using the reference coupler,
- the artificial ear has much wider application both in terms of new earphone design and extended frequency range, and therefore likely to become increasingly important in the future,
- adopting the artificial ear as the sole calibration device is a possibility and would result in certain technical improvements, but also requires consequential changes in ISO 389-1.

5. CONSULTATION OF USERS

Following the findings of Lawton (2003)[35] a consultation was carried out to elicit views from the user community on consequences of adopting the artificial ear as the sole reference device for the calibration of audiometric earphones, and of the use of one set of RETSPL values, those published in ISO 389-1 for the artificial ear.

Around 40 organisations or individuals were consulted to obtain their views on the general acceptability of the proposal, the perceived benefits, the problems they could foresee if this were to be adopted and whether this step would be seen as an improvement. These were predominantly hospital and university audiology departments but also included specialist technical organisations supplying audiological and hearing aid equipment and calibration and repair services. Ultimately an answer was sought to the question of whether the proposals received widespread approval.

The use of the artificial ear as sole device for measurement of supra-aural earphones was seen to be acceptable to everyone consulted, as was the use of one set of RETSPL values. It was generally felt that this would be of benefit, both simplifying and rationalising the calibration requirement and could resolve some of the present discrepancies and ambiguities.

The issue of continuity caused questions to be raised over the consequences of this change. It is expected that barely discernable changes will result from adoption of this proposal. Differences of the order of 0.5 dB in the calibration of TDH-39 earphones on the respective ear simulators have been measured. The exception is 6 kHz where a problem with the calibration of TDH-39 on the reference coupler is known to exist. However further work will be required to fully establish the equivalence of measurements on the two devices. One other option that has been proposed is that the present RETSPL values be corrected to better reflect a true threshold level. This would appear to have far wider consequences and would have much greater impact on the continuity of hearing threshold measurement.

Some reservations were expressed regarding the financial consideration of the change, in terms of the cost of purchase and calibration of new equipment. This is only an issue where a calibration facility has been established to calibrate audiometers fitted with TDH-39 earphones exclusively. It therefore only requires the use of the reference coupler. The proposal would mean this is abandoned and replaced with an artificial ear and possibly some other associated equipment. This situation is quite rare but could exist for example where a manufacturer or supplier only calibrated instruments they sell and these are always fitted with THD-39 earphones. In actual practice it is common for a variety of earphones to be calibrated and most services already own an artificial ear. Any investment required could be justified in terms of the additional capability the artificial ear provides; the ability to calibrate newer types of supra-aural earphones and circumaural earphones which are used for normal and high frequency audiometry. Another implication of the change would be the retraining of staff and quality system requirements, which could also require a substantial investment.

The issue of acceptability of this proposal in foreign markets was also raised, especially the USA where the IEC 60318-3 or equivalent device is widely if not solely used for supra aural earphone measurement.

Overall reaction to the proposal ranged from general acceptance to enthusiastically supportive. No organisation opposed the initiative to bring about a change. The main identifiable benefits included;

- a reduction in the amount of equipment needed to calibrate audiometers,
- a significant reduction in routine calibration and maintenance required,
- improvements in usability and reduced risk of microphone damage. The reference coupler uses a microphone with exposed diaphragm throughout the frequency range,
- elimination of ambiguity over which ear simulator and set of RETSPLs to use for supra aural earphones, removing the origin of the confusion that persists,
- although not perfect, the artificial ear provides a better simulation of the human ear and therefore a more realistic calibration of the earphone,
- a more realistic ear simulator will lead to improved reliability in hearing assessment, in particular removing the phantom and often mis-interpreted 6 kHz notch evident in many audiograms produced with TDH-39 earphones,

- the artificial ear is also specified as the calibration device for circumaural earphones and will in the future be extended to cover the full frequency range for these earphones.

The drawbacks that were identified were;

- the cost of any adapting calibration facilities to comply with the recommendations, including new equipment, retraining of staff, revised calibration procedures and quality system. These are however one-off costs,
- the normative data for hearing threshold is largely based on original measurements made with the reference coupler. The same volume of data does not exist for the artificial ear,
- the artificial ear is a more complex device than the reference coupler and may not be so easy to maintain as the reference coupler,
- the reference coupler may have other uses outside of pure-tone audiometry and would not be completely obsolete if these recommendations were implemented.

The consensus view that was drawn from this consultation exercise was therefore to proceed with the recommendations that lead to a single ear simulator being specified for hearing threshold measurement. Based on these findings it is now possible to formulate recommendations for the working group reviewing ISO 389-1.

6. OPTIONS AND RECOMMENDATIONS FOR ISO

ISO 389-1 is under review and revisions are being considered by a working party within the technical committee (TC43, WG1). Various options exist for this revision, which can be partly informed by the outcome of this project. These include, roughly in order of increasing disruption:

1) Doing nothing and reaffirming the Standard in its current, unaltered form.
2) Attend to minor editorial changes, but leave the substance and numerical data for RETSPLs unchanged.
3) Adjust RETSPL values based on the latest available data, thereby removing data known to be in error.
4) Undertake a co-ordinated programme of measurements to re-establish the threshold of hearing and determine new RETSPL values.
5) Remove the RETSPL values for the reference coupler, thereby preventing the use of Bayer DT48 and TDH 39/39P earphones in pure-tone audiometry. All remaining earphones will then be calibrated using the artificial ear.
6) Remove the RETSPL values for the reference coupler, but allow *all* supra aural earphones to be calibrated using the artificial ear using the existing RETSPL values in ISO 389-1 for this ear simulator.
7) Proceed as in 6) above, but specify newly determined RETSPL values for the artificial ear.
8) Remove the need for the ISO 389 series altogether by basing hearing threshold measurement simply on sound pressure level. This presents technical challenges and requires significant instrumentation developments, but ultimately could be achievable.

Further options may also exist. There are two main issues to consider in selecting an option. First, the question of which ear simulator(s) to specify, and second whether to revise the RETSPL(s). The second is outside of the scope of this work, but the issue of continuity and consequences of changes clearly need to be considered in making any decisions. Ultimately it depends on what one wants for the RETSPL. Some consider that this should represent the expected threshold that would be measured for an adult with normal hearing. In this case no other information other than the measured hearing level is required to make a diagnosis of hearing loss. However the RETSPLs and criteria for hearing loss compensation would need to be reviewed periodically to ensure that the hearing level of the normally-hearing population remains adequately described. The alternative is to consider the RETSPL as an arbitrary reference level against which hearing can be assessed, approximating, but not necessarily equivalent to, the normal hearing threshold. In this case no review should ever be necessary, though it is an interesting social study to see how hearing levels appear to be changing relative to this datum.

Returning to the first question, the work presented in this report clearly indicates that the UK view' as established through the consultation, is for ISO 389-1 to be revised so that:

the IEC 60318-1 artificial ear becomes the sole device for measurement of all types of supra aural earphones, and should be used in conjunction with the RETSPL values currently published in ISO 389-1 for the IEC 60318-1 artificial ear (at least for the revision proposed currently).

This corresponds to option 6) in the list above.

However it is not proposed that the reference coupler be removed from the standard altogether. It is still widely used in parts of Europe and especially in the USA, for quality control and routine testing. Until measurement practices have had time to adapt to the change, ISO 389-1 should specify the artificial ear for all earphones, but include data for the reference coupler and any other couplers as necessary in an informative annex to the standard.

7. CONCLUSION

This work has considered in detail the feasibility, both technically and from a user perspective, of adopting a single ear simulator as the basis of earphone calibration in pure- tone audiometry. The technical feasibility was reported by Lawton (ISVR partner) and concluded that;

- while the THD-39 earphone was found to still perform well, there are no well-founded technical arguments for why it must continue to be calibrated using the reference coupler,
- the artificial ear has much wider application both in terms of new earphone design and extended frequency range, and is therefore likely to become increasingly important in the future,
- adopting the artificial ear as the sole calibration device is a possibility and would result in certain technical improvements, but also requires consequential changes in ISO 389-1.

NPL has looked further at the issues surrounding the requirement for *two* ear simulators to cover the range of earphones in use and found a number of anomalies and inconsistent practices reported in the literature. These would ultimately lead to different measures of the same person’s hearing.

Based on these findings, the proposal that the artificial ear be used as the sole device for measurement of supra-aural earphones, and the consequences of such a change, were put to the measurement community for their comment. Benefits to the users were clear and unanimous support for the proposal was expressed, albeit with certain reservations in a small number of cases.

It is therefore possible to make a recommendation to ISO that;

- ISO 389-1 be revised so that the artificial ear becomes the sole device for measurement of all types of supra aural earphones,

- the RETSPL values currently published in ISO 389-1 for the IEC 60318-1 artificial ear should remain unchanged,
- the reference coupler be placed in an informative annex with RETSPL values for this device including RETSPL values published in ANSI S3.6, for historical purposes and continuity.

For the foreseeable future adopting the artificial ear provides the best solution. In the longer term, a move to measuring hearing thresholds in terms of actual sound pressure level would remove the need for the ISO 389 series altogether. Audiometers could then be calibrated in terms of this, assuming even more realistic ear simulators are developed, or earphones developed that facilitate direct measurement of in-ear sound pressure level. This would also mean that hearing is measured purely in terms of a physical unit, with no reliance on subjective empirical data that may be dependent on time and social conditions.

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