In-situ audiometry: How close is it to conventional audiometry?

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Abstract
Technology in the hearing aid industry is ever changing. One of the many features that may improve accuracy of hearing aid fittings and patients’ satisfaction is the inception of in-situ audiometry, which allows the clinician to measure hearing thresholds with a hearing aid in the patient’s ear. Objective: The present study aimed to investigate the validity of in-situ audiometry measured with a behind-the-ear hearing aid coupled to a customized earmould relative to conventional thresholds measured using supra-aural head phones. Study design: A total of 24 ears from 15 participants with varying degrees of sensorineural hearing loss ranging from moderate to severe, were selected for the study. Pure tone hearing thresholds and real-ear-to-dial-differences were measured for both conventional and in-situ thresholds across 250 Hz to 6 kHz. Results: Slight but significant mean differences (p < 0.05, paired t-test) of 3.2 and 3.4 dB between conventional and in-situ thresholds at 2000 and 6000 Hz were found before adding REDD corrections with in-situ thresholds yielding better (lower) thresholds. Except at 250 Hz in dB HL, individual threshold variability between conventional and in-situ threshold measurements was within or equal to ±10 dB for >95% of ears before and after adding REDD corrections. Large inter-participant variation in measured ear canal SPL was noticed at 250, 500, 4000 and 6000 Hz when measured in-situ compared to headphones, which was attributed to differences in earmould vent sizes provided for different degrees of hearing loss at the low frequencies and probe placement in the high frequencies. Conclusion: Overall in-situ audiometry proved to be valid especially in individuals with symmetrical sensorineural hearing loss. Although there are statistically significant differences, they are within clinically accepted standards. Furthermore, thresholds measured in ear canal SPL will be more comparable as any changes in hearing threshold levels in either of the measurements will be reflected by an inverse change in measured ear canal SPL during REDD measurements.

Key words: sensorineural, hearing loss, hearing aid, real-ear-to-dial-difference

Introduction
Traditionally, pure tone hearing thresholds are measured in hearing levels (dB HL) by using a standard audiometer. This behaviourally obtained frequency-specific and ear-specific information can be converted to sound pressure levels (dB SPL) by applying average or individual real-ear-to-dial-difference (REDD) or real-ear-to-coupler-difference (RECD) values while fitting hearing aids. Alternatively, hearing aid fittings can also be based upon hearing thresholds obtained using digital hearing aids by taking an individual’s anatomy and physiology of the ear canal into consideration. This procedure is termed in-situ audiometry. Unlike conventional audiometry, in-situ audiometry utilizes manufacturers’ fitting software to adjust the stimuli levels and uses the hearing aid receiver as a transducer to deliver the stimulus. The patient is instructed to respond in a manner similar to the one followed during conventional audiometry. It is assumed that hearing aid fittings based on in-situ thresholds derive accurate prescriptive gain-frequency response as this procedure takes into consideration the anatomy, the physiological changes in ear canal, depth of earmould or instrument in the canal, venting effects and acoustic coupling to the hearing instrument. This may in turn lead to accurate fitting, greater patient satisfaction and fewer returns.

Over the last decade, technology in hearing aids has undergone significant improvements to meet the demands of the end user (1) (e.g. wireless compatibility, adaptive directionality). While there was a great amount of research that documented the usefulness of these features (2,3), little attention has...
been paid to studying the benefits and limitations of in-situ audiometry. To date there are few articles in the literature relating studies of the validity of in-situ audiometry and these have mixed results (4–7). For example, one study (4) showed a significant difference of 6 and 9 dB at 1 and 2 kHz between in-situ thresholds measured with the Widex Inteo I-19 behind-the-ear (BTE) hearing aid coupled to an insert ear tip, relative to conventional thresholds measured with an insert ear tip; whereas, another study (5) showed insignificant differences with the receiver-in-the-aid (RITA) and receiver-in-the-canal (RIC) using three different manufacturers. Furthermore, the author noticed that two out of three manufacturers’ in-situ thresholds closely matched their conventional thresholds. Although both these studies investigated the validity of in-situ audiometry in hearing impaired participants, the major difference was that the former study used insert tips whereas the latter used TDH 39 headphones to measure conventional thresholds. However, both these studies lacked information about REDD or REDD corrections between in-situ and conventional thresholds, as there could be differences in SPL generated by different transducers for a given dB HL (6). This issue was addressed by a more recent study (7) where the authors compared in-situ thresholds measured with instant fit open and closed domes relative to conventional thresholds measured with insert tips before and after adding REDD corrections. Interestingly, their results revealed a significant difference between in-situ and conventional thresholds up to 1500 Hz before adding REDD corrections. At 250 Hz, the average threshold difference was about 30 dB for open dome and 10 dB for closed domes. However, the results were more comparable after converting the thresholds to ear canal SPL by adding individual REDD values. Moreover, the test-retest reliability of in-situ thresholds was within 4.5 dB and 9 dB in 88–96% and 98–100% of individuals, respectively. The authors suggested using a stringent protocol to control ambient noise especially while measuring in-situ thresholds with open and closed domes as these coupling options provided less attenuation of ambient noise. Another study (8) investigated the test-retest reliability of in-situ audiometry with a Widex SP3 hearing device coupled to an insert receiver in normal hearing individuals and found insignificant mean differences. The mean difference was found to be within 1 dB across 0.5–4 kHz and the percentage agreement between two threshold measurements was in the range of 93%–100% using ±5 dB criteria.

It is evident from the aforementioned studies that in-situ audiometry proved to be valid and reliable with specific types of hearing aid models using different acoustic coupling options, but there are no published data from investigations of the validity of in-situ audiometry using the patient’s own earmould by taking natural anatomical and physiological changes of the ear canal into account.

Therefore, the present study aimed:

- to assess the validity of in-situ audiometry using the patient’s own earmould relative to conventional audiometry measured using supra-aural headphones, before and after adding REDD corrections;
- to study individual variation in in-situ thresholds relative to conventional thresholds using ±10 dB criterion level, before and after adding a REDD correction.

Method

Participants

A total of 15 participants (24 ears (seven females and eight males)) with an age range of 48 to 82 years (mean, 66.1 years) were recruited for the study. All participants had varying degrees of bilateral symmetrical sensorineural hearing loss ranging from moderate to severe with an air-bone gap of <10 dB in each ear and an asymmetry not exceeding 30 dB HL between ears to avoid the need for air conduction masking. A conservative value of 30 dB HL, instead of 40 dB HL for air conduction masking, was selected to ensure there was no cross-hearing into the non-test ear. All the participants were using digital behind-the-ear (BTE) hearing aids coupled to customized hard earmoulds with 0.6 to 2.5 mm venting provided, based upon the hearing aid fitting software’s information as per the degree and configuration of hearing loss. None of the participants had any significant neurological complication. Prior to audiometry, participants underwent otoscopic evaluation to check for any occluding ear wax and the integrity of the tympanic membrane. All testing was performed as a part of routine clinical evaluation and the participants were selected from Tan Tock Seng Hospital’s Otolaryngology outpatient clinic, Singapore. The study has been approved by the National Health Care Group-Domain specific review board.

Instrumentation

Conventional audiometry. Otoscopic examination was performed prior to conventional audiometry using a Welch Allyn handheld otoscope. Subsequently, using an AC-440 PC-controlled clinical audiometer, air conduction thresholds for each ear were obtained at all octave frequencies up to 6000 Hz, followed by a 1000-Hz recheck. Patients were tested in a double-walled soundproof room. The audiometer was
Table I. Mean, standard deviation (in brackets), mean difference and p-value for both in-situ and conventional condition.

<table>
<thead>
<tr>
<th>Condition</th>
<th>250 Hz</th>
<th>500 Hz</th>
<th>1000 Hz</th>
<th>2000 Hz</th>
<th>4000 Hz</th>
<th>6000 Hz</th>
</tr>
</thead>
<tbody>
<tr>
<td>In-situ</td>
<td>53.1 (21.4)</td>
<td>57.2 (17.3)</td>
<td>64.5 (13.1)</td>
<td>62.0 (12.2)</td>
<td>70.2 (10.4)</td>
<td>70.2 (11.0)</td>
</tr>
<tr>
<td>Conventional</td>
<td>55.4 (15.5)</td>
<td>57.2 (14.2)</td>
<td>64.1 (14.8)</td>
<td>65.2 (11.8)</td>
<td>70.2 (10.9)</td>
<td>73.6 (10.7)</td>
</tr>
<tr>
<td>Mean difference</td>
<td>-2.3</td>
<td>0.0</td>
<td>0.4</td>
<td>-3.2</td>
<td>0.0</td>
<td>-3.4</td>
</tr>
<tr>
<td>p-value</td>
<td>0.38</td>
<td>1.00</td>
<td>0.71</td>
<td>0.02*</td>
<td>1.00</td>
<td>0.02*</td>
</tr>
</tbody>
</table>

Mean difference = in-situ minus conventional.
*Significant at 0.05 level.
significant differences between the two measurement conditions. Without a REDD correction the statistical results revealed significant mean differences ($p < 0.05$) of 3.2 and 3.4 dB at 2000 and 6000 Hz with the in-situ thresholds being better (lower) compared to conventional thresholds. Although there was a statistically significant difference at these frequencies, they are clinically negligible in impacting the gain-frequency response curves during hearing aid fitting or the subjective perception of sound quality for hearing aid users. These changes are also reflected in REDD measurements with in-situ SPL being statistically ($p < 0.05$) higher by 2.6 and 4.5 dB, suggesting that these threshold differences are predominantly due to changes in ear canal SPL. In addition, the same trend was observed at 250 Hz with in-situ being better (lower) by 2.3 dB compared to conventional thresholds and REDD measurements being higher by 3.2 dB. When comparing between mean thresholds in SPL, the differences were within 1 dB across 250–6000 Hz, emphasizing that thresholds measured in dB SPL are closer than those measured in dB HL.

Individual threshold variability, measured in HL and SPL between the two measurement conditions using $\pm 10$ dB criterion level, are shown in Table II. The mean REDD values for in-situ and conventional conditions, along with inter-participant variation, are depicted in Table III. When comparing thresholds in HL, the variability was $\pm 10$ dB for more than 95% of ears from 500 to 6000 Hz and decreased to 66.6% of ears at 250 Hz. The remaining participants had variations greater than 10 dB. At 250 Hz, the maximum variation of 25 dB was observed for two ears, followed by 20 dB for two ears and 15 dB for four ears. When compared in SPL, the variability of $\pm 10$ dB increased to 91.6% of ears at 250 Hz, but was maintained consistently in more than 95% of ears across 500–6000 Hz. This greater variation in HL at 250 Hz could be related to larger inter-participant variation in measured ear canal SPL. As illustrated in Table III, inter-participant variation for the measured ear canal SPL was 12.1 and 7.2 dB at 250 and 500 Hz in the in-situ condition, compared to 6.2 and 4.3 dB at the same frequencies in the conventional condition.

**Discussion**

This study aimed at determining the differences in conventional thresholds measured with supra-aural headphones and in-situ hearing thresholds measured with Phonak Bolero SPBTE hearing aids with earmoulds in participants with symmetric sensorineural hearing loss. The statistical analysis showed slight but significant mean differences of 3.2 and 3.4 dB at 2000 and 6000 Hz between the two measurement conditions when thresholds were measured in dB HL, with in-situ thresholds yielding better (lower) results compared to conventional thresholds. These differences could be predominantly due to the fact that a greater SPL is generated in the ear canal when the stimulus is driven through the hearing aid transducer compared to conventional headphones. This was quantified by measuring individual REDD where it revealed that the ear canal SPL was higher by 2.6 and 4.5 dB at 2000 and 6000 Hz during the in-situ condition compared to the conventional condition. Therefore, it is reasonable to assume that lesser sound output was required to generate the same sound pressure level in the ear canal leading to better (lower) hearing thresholds for the in-situ condition. However, it is important to note that these threshold

<table>
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<th>6000 Hz</th>
</tr>
</thead>
<tbody>
<tr>
<td>In-situ</td>
<td>15.3 (12.1)</td>
<td>11.1 (7.2)</td>
<td>9.5 (3.1)</td>
<td>18.5 (2.9)</td>
<td>15.6 (4.0)</td>
<td>19.5 (6.4)</td>
</tr>
<tr>
<td>Conventional</td>
<td>12.1 (6.2)</td>
<td>10.8 (4.3)</td>
<td>10.4 (2.5)</td>
<td>15.9 (2.6)</td>
<td>16.6 (5.0)</td>
<td>15.0 (6.3)</td>
</tr>
<tr>
<td>Mean difference</td>
<td>3.2</td>
<td>0.3</td>
<td>-0.9</td>
<td>2.6</td>
<td>-1.0</td>
<td>4.5</td>
</tr>
<tr>
<td>$p$-value</td>
<td>0.12</td>
<td>0.84</td>
<td>0.31</td>
<td>0.00*</td>
<td>0.44</td>
<td>0.01*</td>
</tr>
</tbody>
</table>

*Significant at the 0.05 level.
differences measured in dB HL were within clinically
accepted limits as audiometers have a tolerance limit
of ±3 dB at 125 to 5000 Hz and ±5 dB at 6000 Hz
and above, thereby making it theoretically possible
to see threshold differences as large as 6–10 dB
across the frequencies when tested with different
transducers (12).

Consequently, when mean thresholds were com-
pared in ear canal SPL, these differences further
decreased to less than or equal to 1 dB across 250–
6000 Hz suggesting that individual REDD measure-
ments can potentially address the issue of greater ear
channel SPL at 2000 and 6000 Hz if one is considered
to have an accurate threshold measurement. The
results obtained in this study are in agreement with
previous investigators (7) where they showed the
mean differences measured in SPL were less than or
equal to 2.5 dB between in-situ thresholds measured
with open and closed domes relative to conventional
thresholds measured with insert phones.

With respect to individual threshold variability
between the two threshold measurements, it was
found that variation was within or equal to ±10 dB
for 66.6%, 95.8%, 100%, 95.8%, 100% and 95.6%
ears for HL values and 91.6%, 100%, 100%, 95.8%,
95.8% and 100% for SPL values across 250 to
6000 Hz. This larger variation at 250 Hz in HL
values could be possibly due to larger differences in
measured ear canal SPL. This was corroborated by
noting larger inter-participant variation in measured
REDD values in the in-situ condition, possibly either
due to differences in earmould vent sizes provided
for different degrees of hearing loss or due to differ-
ences in ear canal size (Table III). As the participants
included in this study had a range of hearing loss,
REDD values at 250 Hz were seen to be varying
from 0 dB to 36 dB depending upon the earmould
venting size for various degrees of hearing loss. On
the other hand, although formally investigating
the effects of ear canal sizes on REDD measurements
in this study, one participant with a smaller ear canal
had a threshold variation as large as 20–25 dB and
REDD variation as large as 10–15 dB with in-situ
thresholds being better (lower) and ear canal SPL
being higher at 250 Hz.

Assuming that in-situ thresholds measured with
customized earmoulds closely resembled measure-
ments performed with insert phones, the results of
this study are in agreement with a previous study
(13) where the authors found no significant differ-
ence between hearing thresholds measured with
supra-aural ear phones and insert receivers in
children and adults. The data in this study suggest
that hearing thresholds can be reliably obtained using
in-situ audiometry during hearing aid fittings. How-
ever, appropriate REDD measurements might be
required if the clinician notices a large threshold dif-
ference between the two measurement conditions.

Table III shows the mean REDD values along
with inter-participant variation for two measurement
conditions. The mean difference in REDD values
varied from −0.9 dB at 1000 Hz to 4.5 dB at 6000 Hz.
As observed from Table III, the variability is large
particularly at 250, 500, 4000 and 6000 Hz, suggest-
ing the possibility that it is due to differences in
ear mould vent sizes or leakage of sound around the
transducer especially at low frequencies and the
positioning of the probe tube at high frequencies.
Surprisingly, however, the overall mean REDD
values appeared to be larger by 3.2 dB in the in-situ
condition compared to the conventional condition at
250 Hz. This might be because the lower REDD
values noted in participants with mild to moderate
low frequency hearing loss due to sound leakage
through the vents, might have been offset by higher
REDD values noted in participants with moderately
severe to severe hearing loss, thereby leading to
overall higher mean values in the in-situ condition
compared to the conventional condition. However, a
formal investigation of the effects of earmould vent
sizes on REDD measurements might address this
hypothesis.

On the other hand, as the procedure of probe
placement in the present study ensured that the
distance from the intertragal notch to the tip of the
probe tube was constant across subjects, it might be
possible that the distance from the diaphragm of the
headphone, from earmould to the ear drum or from
the tip of the probe to the ear drum, might vary due
to differences in ear canal length leading to standing
wave errors at higher frequencies. Nevertheless, this
inter-participant variation of ear canal SPL measured
with TDH 39 headphones, appeared to be slightly
less compared to the previous study (14) where the
authors revealed variations as large as 4.6 and 7.3 dB
at 2000 and 4000 Hz compared to 2.6 and 5.0 dB in
the present study. In contrast, the variability of ear
canal SPL measured with a hearing aid appeared to
be significantly larger compared to the previous study
(7) where the authors in their study revealed vari-
ations of 5, 3.2, 2.9 and 4.1 dB at 250, 500, 4000 and
6000 Hz compared to 12.1, 7.2, 4 and 6.4 in the
present study. Furthermore, the mean REDD values
in the in-situ condition were higher by 3.5 dB at 1000
Hz to 9.5 dB at 6000 Hz compared to the previous
study (7). This makes it difficult to accurately predict
the individual REDD values measured using a
hearing aid transducer from the averaged data that
are stored in some commercially available REM
equipment.

Target gain curves derived using in-situ thresh-
olds are predicted to be more accurate as they take

In-situ audiometry 5
individual ear canal shape and size, insertion depth, venting effects and earmould tubing into consideration. This results in a more accurate first fit and greater acceptance by the patient, thereby enabling the clinician to cater for more clinic time on hearing aid counselling and setting realistic goals, rather than on fine tuning. Moreover, in-situ audiometry can also be a time-efficient feature by eliminating the need to measure hearing thresholds using standard audiometry and transferring the data to hearing aid fitting software especially for fine tuning hearing aids. Given the surge in hearing aid technology over the past few years, one would not be surprised to anticipate self-fitting hearing aids in the coming years where in-situ audiometry would play a major role by allowing the wearer to self-measure the hearing thresholds in a reliable manner for adjusting the hearing aids (6). Another potential advantage of in-situ audiometry is its ease and feasibility to be carried and administered during home visits in remote areas or in developing countries where the availability of audiology services is limited. However, the nature and type of hearing loss needs to be understood beforehand to perform in-situ audiometry in such cases. The results from this study can only be generalized to adults using Phonak BTE hearing aids with customized earmoulds. Nevertheless, it is wise to monitor the reliability of in-situ thresholds over time as transducers may drift in terms of quality with extended usage (5). Further research is warranted using customized hearing aids, as the coupling options in those models are entirely different compared to BTE hearing aids. It is expected that in-situ thresholds can be even better, especially with completely-in-the-canal hearing aids as they are placed close to the eardrum resulting in a greater sound pressure level (SPL). However, evidence supporting this area is paramount for clinicians fitting hearing aids.

Although in-situ audiometry, with REDD corrections, provides a viable option in measuring hearing thresholds, it should never be a replacement for standard audiometry for clinical purposes, nor should the clinician solely depend upon it for hearing aid fittings.

Conclusion
The data in this study suggest that in-situ thresholds can be reliably obtained using Phonak BTE hearing aids coupled to customized earmoulds relative to conventional hearing thresholds measured under supra-aural headphones. Although there was a statistically significant difference between in-situ and conventional thresholds in dB HL at 2000 and 6000 Hz, they were clinically negligible in this small group. Variability in individual thresholds was similar for both HL and SPL values from 500 to 6000 Hz, but slightly increased at 250 Hz. The mean REDD values measured in the in-situ condition were slightly but significantly higher at 2000 and 6000 Hz compared to conventional REDD values. Finally, thresholds measured in ear canal SPL will be more comparable, as any changes in hearing threshold levels in either of the measurements will be reflected by an inverse change in measured ear canal SPL during REDD measurements.

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