Boothless Aided Audiometry: A Pilot Study

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Abstract

Background: Although free-field aided audiometry is not the gold standard of hearing aid verification because of its many limitations, it is still circumstantially needed. The conventional method of sound-field aided audiometry requires a sound-proof booth. However, as clinicians face a high-volume of audiometric tests ordered daily at the otolaryngology clinic, a sound-proof booth may not always be available when needed. This study aims to explore if out-of-booth free-field aided audiometry can be just as reliable as the conventional method.

Methods: A pilot exploration of 10 patients (20 ears), with at least a moderate degree of bilateral symmetrical sensorineural hearing loss was conducted. Patients were recruited during their follow-up hearing aid appointments with their audiologist. All patients had been fitted with hearing aids for at least 6 months in duration, and their hearing aids were optimized.

Results: Out-of-booth aided audiometry for the main frequencies of interest was reliable with good correlation between the two methods at primary frequencies (500 Hz–4 KHz). However, results in the high frequencies were less reliable and needs to be interpreted cautiously.

Conclusion: Out-of-booth sound-field audiometry may be a quick and reliable method that can be used to fulfill its intended purpose with the added advantage of not needing an arguably expensive audiometric booth. However, not all frequencies of interest can be assessed with reliable measurements. Further larger studies are needed to validate the reliability of boothless sound-field audiometry to meet evolving healthcare needs.

Keywords
Aided audiometry, sound field, audiology, audiometric booth

Introduction

Performance verification of hearing aids can be assessed through a few different methods, including word recognition, probe-microphone measurements, aided sound-field thresholds and functional gain.¹ Although aided sound-field thresholds reflect the patients’ response to hearing aid amplification, it has many limitations including reflecting amplification for low-input levels.² However, this method of verification is still situationally needed. In the paediatric population, probe microphone measurements are not always possible as this population group may not be compliant to keeping still and quiet throughout the assessment. Furthermore, speech materials are also not available for children less than 2 years of age as they do not have appropriate speech and language skills for standardized recording of speech tests. Hence, there is a need to incorporate other quick measurements such as Real-Ear-to-Coupler Difference (RECD), test-box hearing aid verification, behavioural aided audiometry and functional gain tests³ to circumvent this problem. In patients with ear implants, these tests are further employed for part verification of effectiveness of cochlear, middle-ear implants and bone conduction devices. Aided audiometry may also be used as part of cochlear implant candidacy assessment in hearing-aid users, suggest a sudden change in hearing thresholds, reveal faults with the hearing aids or assess frequency transposition in hearing aids.⁴ The standard narrative is to perform aided audiometry in a calibrated sound booth. However, this is subjected to the availability of the sound booth, which is unpredictable especially in clinics with high patient workload. In our experience, an average of more

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than 12,000 hearing tests are ordered each year, with a steadily increasing trend due to the rapidly ageing population who need hearing services. This makes the audiometric booths unavailable most of the time for sound-field aided audiometry. Innovative methods are hence needed to circumvent this problem to increase convenience and ensure continuity of services for our patients. This pilot study explores the results of a sound-field aided audiometry obtained out of booth with results from a standard audiometric booth in a small group of patients with hearing aids.

Methods

A service evaluation study was carried out with all procedures in accordance with the 1964 Declaration of Helsinki. This study was granted an exemption by the Centralised Institutional Review Board because data collection was part of service evaluation where there is no change to the standard service being delivered (where standard service refers to aided audiometry), with no anticipated risks to the study participants. We evaluated aided audiometry as a standard service by comparing two different methods in this pilot exploration. Boothless-aided audiometry needs to be validated locally before future inclusion in standard practice. A convenience sample of patients who were fitted with bilateral receiver in the ear (RIE) hearing aids for a duration of at least 6 months, with real-ear measurement (REM) targets matched were prospectively recruited at the otolaryngology clinic during their follow-up hearing aid appointments. All patients had a hard acrylic in-canal mold, with a symmetrical bilateral moderate-to-severe sensorineural hearing loss. The audiometric profile was not steeply sloping, and no aggressive feedback cancellation nor frequency compression/transposition were needed. Average data-log was 9.8 h accompanied with patients’ self-reported daily use. Aided sound-field audiometry was tested either in the Acoustic National Standard Institute (ANSI)–calibrated audiometric booth or in a clinic room with calibrated sound-field speakers. 10 patients (20 ears) were recruited and tested, and their aided-audiometric results were compared. Aided audiometric thresholds were obtained alike conventional pure tone audiometry with validated psychoacoustical methods, using a 10 dB down and 5 dB up (two down one up) threshold-seeking paradigm. A consistent two of out of three responses is taken to be valid. Recruited patients alternated between going for in-booth or out-of-booth aided audiometry test equally, in no order of preference during their routine hearing aid follow-up appointments on the same day. It was ensured that no further adjustments were made to the patients’ hearing aids prior to testing.

Warble tone as a stimulus was selected to avoid any free-field standing wave effect especially for the high frequencies. Although all hearing profiles were noted to be symmetrical and there is minimal risk of cross-over, occlusion of the non-test ear will ensure its complete exclusion. Occlusion effect (which is an enhancement of bone-conducted sound waves) is not of concern here as this involves a near and reverberant field of air-conducted sound energy. Cross-over of free-field sound energy happens after head diffraction (head shadow effect) if the contralateral non-test ear has significantly better hearing thresholds. Although unnecessary (due to the symmetrical hearing profiles), each ear was tested separately with the hearing aid on the non-test ear switched off. A headphone padding was also used to cover the non-test ear to ensure complete exclusion from participation.

Audiometric Booth (In-Booth) Calibration Standards and Orientation of Speakers

Standard audiometric booths were calibrated according to the American National Standard Institute (ANSI) S3.6-1996, revised and reaffirmed in 2008. Annual acoustic checks and maintenance are performed by acoustic engineers according to the International Standardized Organisation (ISO) 16283-1:2014, with a noise criterion (NC) of 25 and maximum permissible noise levels depending on the 1/3 octave frequencies (average 30 dBA). 15 x 15 cm free-field speakers were arranged at a 90-degree azimuth from the speakers, with a 1-m distance from the patients (Figure 1). Patients were seated on a fixed chair with the centre of the chair directly above a floor marking for consistency. Interacoustic Affinity Suite audiometer software version 2.14.0 was used during calibration and set-up.

Clinic Room (Out-of-Booth) Calibration Standards and Orientation of Speakers

Only one free-field speaker was used, placed on top of the table facing the patients at 0-degree azimuth. A probe microphone is attached and fixed on top of the speaker and calibration was performed similarly to ANSI standards with a maximum permissible noise threshold set for clinicians to monitor dynamic noise floor levels during aided audiometry (Figure 2). The maximum permissible noise criterion is revealed in Table 1. When noise exceeds thresholds of individual frequencies, clinicians will stop testing until noise levels are acceptable. Speaker is also at a 1-m distance from patients, who were seated on a fixed chair with the centre of the chair directly above a floor marking (Figure 3). As there is a slight height difference from the speaker to the patients’ ear level, the speaker was first elevated by 20” to face the head of the patients. During calibration, the sound engineers placed probe microphones on both pinnae to correct for reference-equivalent threshold sound pressure levels (RETSPL) levels reaching the pinna. The speaker output will be adjusted accordingly to ensure that RETSPL is close to the reference value. This was sequentially performed first with a 1 Khz warble tone at 75 dB SPL followed by each frequency of interest. The RETSPL levels were then compared with the levels obtained in the audiometric test booth at the same frequencies and were within ±5 dB. The similar Affinity Suite audiometer software version 2.14.0 by Interacoustics was used with calibration and set-up done by a technical engineer.

Statistical Analyses

The data were analysed using Statistical Package for Social Sciences (SPSS 21.0; IBM Corp., Armonk, NY, USA). Paired-sample t-tests of significance were conducted to compare the results of both methods to assess for agreement between both methods. Intra-class correlation analyses were
also performed to identify correlation and agreement via a two-step mixed model with absolute agreement. Bonferroni-corrected $P$ value of significance was taken at 0.02. The mean difference in the warble tone average (WTA) between both methods at individual frequencies was calculated to see if it is within the acceptable range of ± 5 dB in test–retest reliability.

**Results**

There were six females and four males with the median age of 68 (range 65–71) and 64 (range 62–67) years, respectively. The intra-class coefficient (ICC) showed good correlation between out-of-booth and in-booth aided audiometry. However, statistical confidence intervals revealed a wide range of ICC for certain frequencies of interest such as at 750 Hz (0.09–0.87) and 6000 Hz (0.10–0.96), suggesting huge variability in its reliability (poor to excellent). Of the frequencies tested, only 500, 1, 2 and 4 KHz had a good ICC of close to 0.8 and above with a 95% confidence range above 0.5, suggesting moderate-to-excellent correlation (Table 2). Furthermore, in these same frequencies of interest, there were no significant differences in the mean values between tests ($P > 0.02$), suggesting good agreement in both methods of aided audiometry for these frequencies tested. Second to that, when tested at 250 and 3000 Hz, there is a similarly quite good ICC of close to 0.8, with the lower range of the 95% confidence interval slightly less than 0.5 (250 Hz: 0.48–0.92 and 3000 Hz: 0.49–0.92). Inter-octave frequencies (750 and

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**Table 1. Maximal Permissible Noise Criterion for Octave and 1/3 Octave Band.**

| Centre frequency (Hz) | Octave band | 1/3 octave band |
|-----------------------|-------------|-----------------|
|                        | 125–8000 Hz | 250–8000 Hz     | 500–8000 Hz | 125–8000 Hz | 250–8000 Hz | 500–8000 Hz |
| 125                   | 29.0        | 35.0            | 44.0        | 24.0        | 30.0        | 39.0        |
| 250                   | 21.0        | 21.0            | 30.0        | 16.0        | 16.0        | 25.0        |
| 500                   | 16.0        | 16.0            | 16.0        | 11.0        | 11.0        | 11.0        |
| 750                   |             |                 |             | 10.0        | 10.0        | 10.0        |
| 1000                  | 13.0        | 13.0            | 13.0        | 8.0         | 8.0         | 8.0         |
| 1500                  |             |                 |             | 9.0         | 9.0         | 9.0         |
| 2000                  | 14.0        | 14.0            | 14.0        | 9.0         | 9.0         | 9.0         |
| 3000                  |             |                 |             | 8.0         | 8.0         | 8.0         |
| 4000                  | 11.0        | 11.0            | 11.0        | 6.0         | 6.0         | 6.0         |
| 6000                  |             |                 |             | 8.0         | 8.0         | 8.0         |
| 8000                  | 14.0        | 14.0            | 14.0        | 9.0         | 9.0         | 9.0         |
and high frequencies (6000 and 8000 Hz) had either poor statistical ICC confidence range and/or a significant difference in the mean values between tests, suggesting either poor correlation and/or agreement between both methods of aided audiometry. The mean difference between out-of-booth and in-booth measurements was also calculated at all frequencies tested. The differences were mostly within ± 5 dB, with the exception at 6 KHz (Figure 4).
Discussion

With the exception of 3000 Hz, the rest of the inter-octave frequencies (750, 1500, and 6 KHz) had either poor agreement or correlation. As the noise floor monitoring was only for the octave frequencies, the poor agreement or correlation could be due to noise exceeding the threshold criterion at these inter-octave frequencies. The high frequencies’ testing may also not be as reliable out-of-booth because high frequencies are impeded by mass more than stiffness. The presence of hard surfaces with dense mass in the clinic room may have affected the higher frequencies tested. Furthermore, although constant monitoring of noise floor allows for intermittent testing within the acceptable noise thresholds, the ‘human errors’ in the judgement of the noise floor in a dynamic sound environment with fluctuating noise levels are not accounted for. However, as there was only one ‘rater’, the errors may be minimized as compared to having more clinicians involved, with greater variability in judgement. In addition, reflection of sound waves due to physical walls and the room acoustics must also be taken into consideration. As compared to a standard audiometric booth, the reverberation time, absorption coefficient, critical distance and hard surfaces that reflect sound waves may affect the eventual output of the free-field speaker. Despite these limitations, the out-of-booth free-field speaker was still calibrated such that the reference-equivalent threshold sound pressure levels (RETSPL) reaching the patients’ location were comparable between both methods as described earlier. Probe microphones at both pinnae ensured that RETSPL reaching RIE hearing aids at the level of the pinnae were comparable between both methods. Although there is a height difference not accounted for in the clinic room (between speaker and patient’s ear), RETSPL values obtained from both methods were close to each other. Such differences may still be clinically significant but is a limitation of the boothless room set-up. The annual workload of audiometric testing is steadily increasing with the ageing population. More than 12,000 counts of pure-tone audiometry are performed yearly, with an average of 33 tests done per day. There is hence a need to meet evolving demands of the audiometric booths, which are used mainly for unaided pure-tone audiometry. If boothless aided audiometry proves to be a reliable method, its use will not be dependent on the availability of the sound booth at any time, especially on a busier day with high volume of patients. This convenience may also be extended to boothless pure-tone audiometry protocol, which has recently been validated. Although aided audiometry can be a scheduled arrangement, occupation of the audiometric booth is still needed, and this will undeniably increase wait time for routine pure-tone audiometry. Furthermore, when patients come for hearing aid appointments, the clinic rooms may not always be located near the audiometric test booths. It may hence be a convenience and an improvement to patients’ experience if they do not have use an audiometric test booth for assessment.

Despite better verification methods for hearing aids (probe microphone measurements), functional gain testing is still needed in certain scenarios, especially in the paediatric and implant population. Validation of the boothless method will allow for greater convenience in the use of this verification test and potentially allow for wide adoption in rural areas without access to medical services with a proper audiology set-up. Aside from the effects of a small sample size, other limitations of this study include ‘rater’ bias as one clinician conducted the aided audiometry. Future studies should attempt to show inter-rater agreement with a larger sample size. Boothless aided audiometry may be a reliable method especially at the main frequencies of interest (500, 1, 2 and 4 KHz). Further prospective studies are warranted to validate such findings with a larger cohort and focus more on controlling variants and confounding factors such as evaluating the acoustic environment of different rooms, and to study different acoustic environments as variables. This will help determine the set-up required for optimal correlation with in-booth audiometry and allow for validation of out-of-booth testing, with ambient noise monitoring as a reliable method.

Data Availability

The data set for this article is accessible on reasonable request from the corresponding author with authorization of the local institution’s department office.

Author Contributions

Chua KWD was responsible for the planning, design, article preparation and all matters related to this study. Yuen HW and Kamath S reviewed the protocol and approved the final article.

Declaration of conflicting interests

The author(s) declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

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Ethical Approval

This study was exempted from Centralised Institutional Review Board because data collection was part of a service evaluation where there is no change to the standard service being delivered, with no anticipated risks to the study participants.

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References

1. Hawkins DB. Limitations and uses of the aided audiogram. *Semin Hear* 2004; 25: 51–62.
2. Seewald R, Moodie KS, Sinclair S, et al. Predictive validity of a procedure for paediatric hearing instrument fitting. *Am J Audiol* 1999; 8: 143–152.
3. Tharpe A, Fino-Szumski M and Bess F. Survey of hearing aid fitting practices for children with multiple impairments. *Am J Audiol* 2001; 10: 32–40.
4. Stelmachowicz P, Hoover B, Lewis D, et al. Is functional gain really functional? *Hear J* 2002; 55: 38–42.

5. American National Standards Institute. *American National Standard: Specification for Audiometers. ANSI S3.6-1996*. New York: American National Standards Institute, 1996.

6. Killion MC. Noise of ears and microphones. *J Acoust Soc Am* 1976; 59: 424–433.

7. Kim J and Koo M. Mass and stiffness impact on the middle ear and the cochlear partition. *J Audiol Otol* 2015; 19: 1–6.

8. Martin JE and Martin WH. Validation of the NUS Boothless Audiometry Protocol, 2021. [https://sahc2021.sg/wp-content/plugins/wad-ahevents/uploads/027_validation-of-the-nus-boothless-audiometry-protocol_jennifer-martin-pdf.pdf](https://sahc2021.sg/wp-content/plugins/wad-ahevents/uploads/027_validation-of-the-nus-boothless-audiometry-protocol_jennifer-martin-pdf.pdf) (accessed May 21, 2021).