Comparing sound field audiometry and free field auditory steady state response in the verification of hearing aid fitting in adults

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Objectives

The aim of this work was to establish hearing aid (HA) functional gain measurements using free field (FF) auditory steady-state response (ASSR) and to compare and correlate sound field (SF) versus ASSR functional gain and unaided and aided hearing thresholds in order to assess the reliability of FF ASSR as an objective tool for the verification of HA fitting.

Participants and methods

This study was conducted on 20 HA user adults with a mean age of 57.09 ± 14.79 years. For each patient, the following were administered: history taking, basic audiological evaluation including pure tone audiometry and immittancemetry, unaided and aided SF audiometry thresholds, and unaided and aided FF ASSR thresholds. The results obtained were then compared. In addition, correlation studies between all the obtained results were carried out.

Results

A highly significant difference was found at 500 Hz only between the SF hearing thresholds and the FF ASSR thresholds among the unaided patients at the four test frequencies (500–4000 Hz). Similarly, aided SF and FF ASSR hearing thresholds showed a statistically significant difference only at 500 Hz. The results of correlation coefficient showed that unaided SF and FF ASSR thresholds were positively significantly correlated at 2 and 4 kHz. In addition, aided SF and FF ASSR thresholds were positively significantly correlated at 1 and 2 kHz. Comparison between the functional gain obtained using both SF and FF ASSR tests showed that there was a highly significant difference only at 4000 Hz.

Conclusion

SF audiometry and FF ASSR unaided and aided thresholds showed very similar results and this indicates that ASSR may be a good alternative method for the measurement of hearing level in infants and children, for whom pure tone audiometry is not possible. FF ASSR appears to be a reliable procedure for the verification of HA fitting and can be used to assess functional gain in difficult-to-test populations and children. Future research on the effect of the electroacoustic characteristics of HAs on aided FF ASSR thresholds is recommended.

Keywords:

audiometry, auditory steady-state response, functional gain, hearing aid, sound field

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Introduction

Audiometry is principally based on psychoacoustic measurement methods where the listener actively reacts to sound signals [1]. There are occasions where it is not possible to carry out psychoacoustic tests, for example on infants, where there is functional hearing impairment or in individuals with some form of mental retardation.

As an objective alternative method for acquiring pure tone audiograms (PTA) for infants and children not suited to behavior observation audiometry, the auditory brain stem response (ABR) can be used. This technique may, however, be difficult in terms of the determination of the participating frequency ranges because the test collects responses from the entire basement membrane with a stimulus tone of a short duration. As a result, the ABR method has little frequency specificity. In addition, ABR tests carried out with click stimuli are of limited use in identifying threshold levels at low-frequency ranges. The ABR test is also inappropriate for determining the characteristics of severe hearing loss over 90 dB HL because this range is beyond its detection limit [2].

The recently reintroduced auditory steady-state response (ASSR) method is a more promising approach, as it provides frequency-specific information facilitated by the use of a modified pure tone for gathering the response. The ASSR is a scalp-recorded auditory-evoked potential that is captured by far-field electrodes such as the ABR [3]. Although there are some similarities to the ABR, the ASSRs have very distinctive features. The ASSR is induced by AM/FM-modulated tonal stimuli [4]. Each stimulus is a continuous tone with a carrier frequency of 0.5–4 kHz that is amplitude (100%) and/or frequency modulated (e.g. 20%) at a modulation frequency of about 80–100 Hz. The power spectrum of the stimulus shows primary energy at the carrier frequency and two side-bands separated from the carrier by the modulation frequency. Automatic measurement is also possible with this method. The test has been evaluated as an objective method to effectively predict hearing level as it offers the advantage of the detection of a wider range of hearing test threshold levels than the ABR method [5].

Early hearing aid (HA) fitting in infants contributes toward the acquisition and development of oral language. For this reason, it is important to have HA fitting protocols specifically designed for very young infants. These protocols will be dependent on electrophysiological methods, because behavioral audiometry is not viable until the age of 5–6 months and, in some infants or young children with developmental delay, not possible at all. In infants and in the adult population, HA fitting consists of three stages: the assessment of hearing sensitivity, the selection of adjustment parameters to restore the hearing perception, and the verification of the prescribed gain for each patient [6].

Assessment of ASSR represents a quick and objective way to establish electrophysiological hearing thresholds at different frequencies. The ASSRs have several advantages in their application in HA fitting: first, they provide assessment of hearing thresholds at different frequencies, second, from these measurements, it is possible to infer the adjustment parameters of HA devices, and third, the acoustic characteristics of the ASSR's stimuli allow verification that the HA is functioning and that the patient perceives and discriminates sounds at a brain level [7].

Functional gain is one of the most used procedures in the verification of the prescribed parameters of HAs. Measurement of the amount of functional gain is calculated as the difference between aided and unaided thresholds at each specific frequency obtained through free field (FF) testing and is defined as the relative decibel difference between the aided and the unaided thresholds. Because this technique is based on voluntary behavioral procedures, the inherent degree of variability to which behavioral thresholds measurements are subjected will also influence functional gain measurements [8].

Mokotoff and Krebs [9] published a pioneer study in which ABR measurements were obtained from adult HA users. The results indicated that aided ABR measurement compared favorably with aided audiological data. Several authors have used the ABR with click or tone burst in order to obtain an objective measurement of the HA response.

Herdman *et al.* [10] have reported that the thresholds obtained from ASSR are as accurate and have the same frequency – specificity as that for tone – burst-evoked ABRs. However, obtaining ABR in the sound field (SF) with amplification is a complex issue. In general, the brief nature of the stimulus used during ABR testing shows high susceptibility to distortion in both the SF speaker and the HA amplifier. Picton *et al.* [11] have reported that ASSRs can be recorded when multiple stimuli are presented simultaneously through an SF speaker and amplified with an HA. Therefore, this procedure seems more useful than procedures using transient stimuli.

The scarcity in the literature on the use of ASSR in the HA fitting process led our research team to carry out this study. The aim of this study is to establish HA functional gain measurements using FF ASSR, and to compare and correlate SF versus ASSR functional gain and unaided and aided hearing thresholds in order to assess the reliability of FF ASSR as an objective tool for the verification of HA fitting. We hope that the information provided by this research will help in establishing a protocol for pediatric HA fitting.

Patients and methods

This study was carried out on 20 HA user adults (14 men and six women) with a mean age of 57.09 ± 14.79 years. They were recruited from the Audiology outpatient clinic of Kasr El-Aini Hospital and the audiological assessment was performed in the same clinic. This research was carried out in the period between June 2011 and February 2012. A written consent to participate in this research was obtained from the participants before commencement of the study. The inclusion criteria constituted of patients with bilateral symmetrical flat moderate, moderately severe, or severe sensorineural hearing loss (SNHL) (as diagnosed by PTA average) with type A tympanogram who were wearing unilateral digital HAs. Thereafter, each patient under study was administered the following:

(1) Full history taking and otologic examination.
(2) *Basic audiological assessment*: PTA was performed at frequencies of 250, 500 Hz, 1, 2, 4, and 8 kHz using a dual-channel clinical audiometer; MADSEN Orbiter 922, version 2 (GN Otometrics, Taastrup, Denmark), with TDH 39 earphones (Audiometrics Inc., Oceanside, California, USA). Immittancemetry including tympanometry and acoustic reflex threshold measurement (ipsilateral and contralateral at frequencies 500 Hz, 1, 2, and 4 kHz) was also performed using a MADSEN Zodiac 901 middle ear analyzer (GN Otometrics), calibrated according to the ISO standards. Immittancemetry was carried out to exclude patients with middle ear pathologies.
(3) *Unaided and aided SF audiometry*: Each patient underwent SF audiometry at frequencies of 500 Hz, 1, 2,

and 4 kHz with the loudspeaker placed at an angle of 45° azimuth and a 1-m distance from the patient's test ear. The same audiometer that was used in PTA audiometry was used in SF testing.

(4) *FF auditory steady-state evoked potential*: The patient was seated on a chair, instructed to relax, close the eyes, and sleep if possible while recording FF ASSR. The multiple auditory steady-state evoked response (MASTER) system (Bio-logic Inc., Mundelein, Illinois, USA) was used for the ASSR testing. This system is a one-channel data collection system that uses three electrodes. The site of electrode placement was prepared with a skin preparing gel. Disc-type silver-coated electrodes were placed with conducting gel. Electrodes were mounted with the active electrode placed on the forehead, the ground electrode on the contralateral mastoid, and the negative (inverting) electrode on the ipsilateral mastoid. Electrode impedance did not exceed 5 kΩ. Response waveforms were added in the time domain and the results were subjected to fast Fourier transform analysis.

The following parameters were used:

(1) *Filter setting*: 1–300 Hz.
(2) *Stimulus*: Four stimuli were presented simultaneously, using a loudspeaker with and without the HA in the FF stimulus presentation condition, placed at 45° azimuth 1 ft from the test ear. The four modulating frequencies (according to the test ear) were 82.031, 84.375, 86.719, and 89.062 Hz for the right ear and 91.406, 93.750, 96.094, and 98.437 Hz for the left ear. Stimuli used were mixed modulation stimuli: amplitude modulation 100%, frequency modulation 20%, and exponential modulation AM^2. The exponential modulation generates larger amplitudes to all frequencies, allowing better observation of the 500 Hz and 4 kHz frequencies [12].

The electroencephalogram signal was passed through a preamplifier and filtered, and then subjected to a fast Fourier transform. The samples of amplitude and phase taken during testing allow statistical analysis to be carried out. The presence or absence of the response was determined automatically from the data using the detection criterion. The level of significance of the responses was monitored after each sweep and evaluated using F ratio statistics. Response was considered as present if the F ratio (probability) was less than 0.05 [13].

Unaided and aided FF ASSR thresholds were assessed for 500, 1, 2, and 4 kHz. Testing was carried out in 10 dB steps; the maximum presentation level was 90 dB nHL. A threshold was defined as the lowest intensity level at which a response was considered to be present. The MASTER technique uses two methods for representation of the response: either a color plot or polar plot graphs. The color plot was used in this study to determine the presence of a response:

(1) Color plot: Three colors could be seen: Green indicates that a response is present. The statistical confidence level of the presence of the response is 95% or higher. This occurs when the F value is less than 0.05. Yellow indicates that a response may or may not be present. The statistical confidence is 90–95%. This occurs when the F value is 0.1–0.05. Red indicates that no significant response is present. The statistical confidence is less than 90%. This occurs when the F value is more than 0.1.

Statistical analysis

An IBM (International Business Machines Corp., Armonk, New York, USA) compatible personal computer was used to store and analyze the data. Analysis of data was carried out using statistical package for scientific studies, version 17, for Windows (Armonk, New York, USA).

The description of variables was presented as follows:

(1) Description of quantitative variables was in the form of mean, SD.
(2) Description of qualitative variables was in the form of numbers and percentage.

Data were explored for normality using the Kolmogorov–Smirnov test of normality. The results of the Kolmogorov–Smirnov test indicated that most of the data were normally distributed (parametric data); thus, parametric tests were used for the comparisons.

(1) Comparison between quantitative variables was carried out using the Student t-test of two independent variables and a paired-samples t-test for repeatedly measured variables. Results were expressed in the form of P values.
(2) The correlation between quantitative variables was determined using the Pearson correlation test. Results were expressed in the form of a correlation coefficient (R) and P values.

The significance of the results was assessed in the form of a P value that was differentiated into the following:

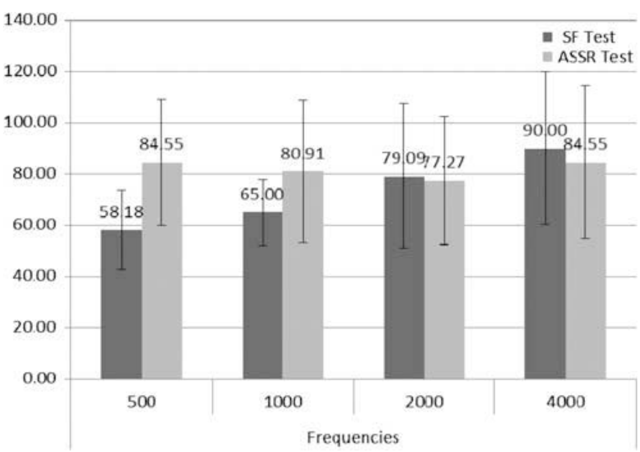
(1) Nonsignificant when P value is greater than 0.05
(2) Significant when P value is up to 0.05
(3) Highly significant when P value is up to 0.01

Results

This research included 20 HA user adults with a mean age of 57.09 ± 14.79 years. It included 14 men (70%) and six women (30%).

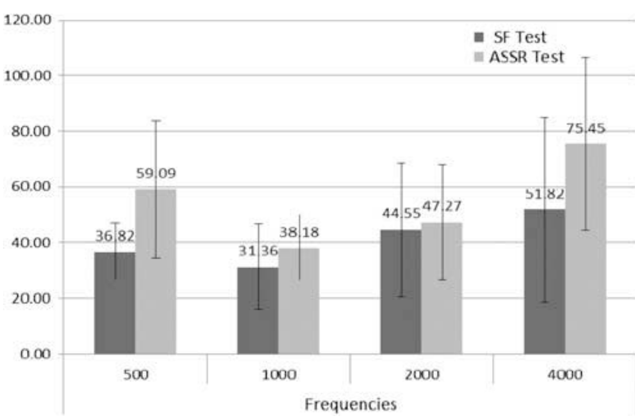
Figure 1 shows the mean and SD obtained for SF hearing thresholds and FF ASSR thresholds among the unaided patients at the four test frequencies (500–4000 Hz). A highly significant difference was found at 500 Hz ($P = 0.007$) only. P values at 1, 2, and 4 kHz were $P = 0.100$, 0.874, and 0.672, respectively.

Figure 1



Mean and SD (dB HL) obtained for sound field hearing thresholds and free field ASSR thresholds among the unaided patients at the four test frequencies (500–4000 Hz). ASSR, auditory steady-state response; SF, sound field.

Figure 2



Mean and SD (dB HL) obtained for sound field and free field ASSR hearing thresholds among the aided patients at 500–4000 Hz. ASSR, auditory steady-state response; SF, sound field.

Table 1 Correlation between sound field and free field auditory steady-state response thresholds at the different test frequencies among the unaided patients

	Unaided patients	
Frequencies (Hz)	Correlation coefficient *R*	*P* value
500	0.179	0.599
1000	0.463	0.151
2000	0.717*	0.013
4000	0.776**	0.005

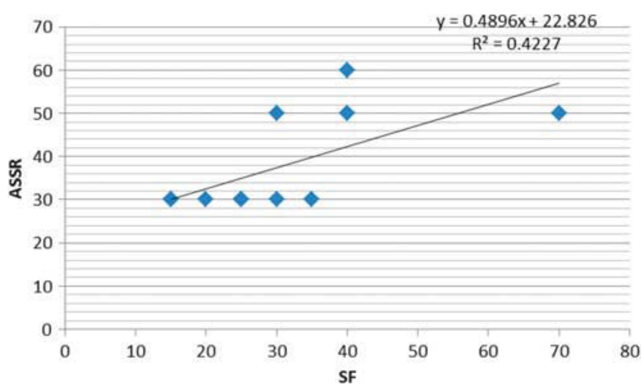
*Significant at $P \leq 0.05$.
**Highly significant at $P \leq 0.01$.

Table 2 Correlation between sound field and free field auditory steady-state response thresholds at the different test frequencies among the aided patients

	Aided patients	
Frequencies (Hz)	Correlation coefficient *R*	*P* value
500	−0.071	0.835
1000	0.650*	0.030
2000	0.696*	0.017
4000	0.398	0.225

*Significant at $P \leq 0.05$.

Figure 3



Correlation between sound field hearing test and free field ASSR test results (dB HL) at 1000 Hz among the aided patients. ASSR, auditory steady-state response; SF, sound field.

Figure 2 shows the mean and SD obtained for SF and FF ASSR hearing thresholds among the aided patients at 500–4000 Hz. The highest mean threshold difference was found at 500 Hz ($P = 0.016$), which showed a statistically significant difference. *P* values at 1, 2, and 4 kHz were $P = 0.258$, 0.778, and 0.099, respectively.

Table 1 shows the correlation between SF and FF ASSR thresholds at the different test frequencies among the unaided patients. The two tests were positively correlated at 2 kHz ($P = 0.013$) and positively highly correlated at 4 kHz ($P = 0.005$).

Table 2 highlights the correlation between SF and FF ASSR thresholds at the different test frequencies among the aided patients. The two tests were positively significantly correlated at 1 and 2 kHz ($P = 0.030$ and 0.017, respectively). Figures 3 and 4 show the positive correlation at 1 and 2 kHz between SF and FF ASSR thresholds among the aided patients.

Table 3 shows the comparison between the functional gain obtained using both SF and FF ASSR tests. The results were highly significantly different only at 4000 Hz ($P = 0.007$). Figure 5 also shows these results.

Discussion

The treatment of those with hearing loss involves the selection and fitting of amplification devices. In difficult-to-test individuals, such as young infants, subjective and objective measures such as functional gain and real ear probe measurements are not always possible. For those patients who do not provide reliable responses to behavioral audiometry, the appropriate selection and fitting of HAs requires the establishment of accurate hearing thresholds by other means. ASSR can be used in the characterization of hearing loss in order to estimate the auditory threshold [14].

In this study, a comparison was made between behavioral SF and FF ASSR hearing thresholds among unaided adult patients. The results showed a highly significant difference between the two tests only at 500 Hz ($P=0.007$) (Fig. 1). FF ASSR results showed significantly higher (elevated) threshold values than SF at 500 Hz.

This is in agreement with Lins and Picton [15], who suggested that the ASSR results should be interpreted with caution at 500 Hz because of internal jittering caused by neurologic asynchronicity, which indicates potential difficulties in determining the threshold levels for low-frequency stimuli compared with high-frequency ones. The same conclusion was reached by other researchers [16–19].

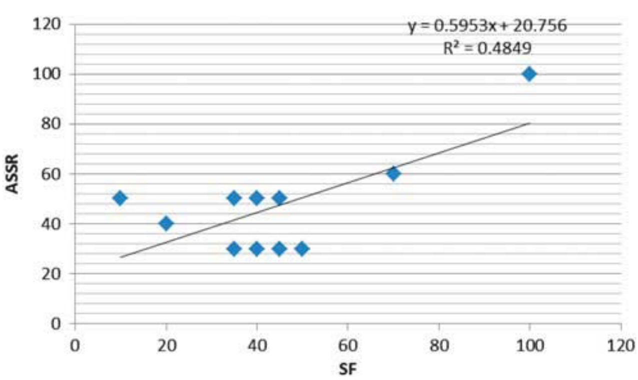
In our research, we found a positive correlation between SF and FF ASSR hearing thresholds in unaided patients with correlation coefficients of (0.717 and 0.776) and ($P=0.013$ and 0.005) at 2 and 4 kHz, respectively (Table 1). The worst correlation was found at 500 Hz and the best correlation at 4 kHz (highly correlated). The mean threshold differences in the 1–4 kHz region varied between 2 and 16 dB.

This is in agreement with the work of Swanepoel and Erasmus [20], who reported that on comparing behavioral and ASSR hearing thresholds, the frequencies 1–4 kHz showed significantly better threshold correlations compared with 500 Hz. The mean threshold differences in their study varied between 2 and 8 dB across frequencies in estimating moderate hearing losses. Ahn *et al.* [21] concluded that PTA and ASSR showed very similar results and indicated that ASSR may be a good alternative method for the measurement of hearing level in infants and children, for whom PTA is not appropriate. Duarte *et al.* [22] reported that there was a significant correlation between the thresholds obtained by PTA and ASSR for all of the tested frequencies, especially for the severe levels.

In contrast, Ballay *et al.* [23] reported that in a group of children with steeply sloping SNHL, the results showed no differences in means at 500 Hz between ASSR and behavioral thresholds. They concluded that ASSR appears to predict the configuration of hearing loss in children with steeply sloping SNHL and overpredicts the severity of the loss by 15–20 dB above 500 Hz at each test frequency (1, 2, and 4 kHz).The difference between their results and the results of the present study may be attributed to the dissimilarity in the configuration of the hearing loss between the two study groups. In their study, less acoustic energy was required at 500 Hz to elicit a response.

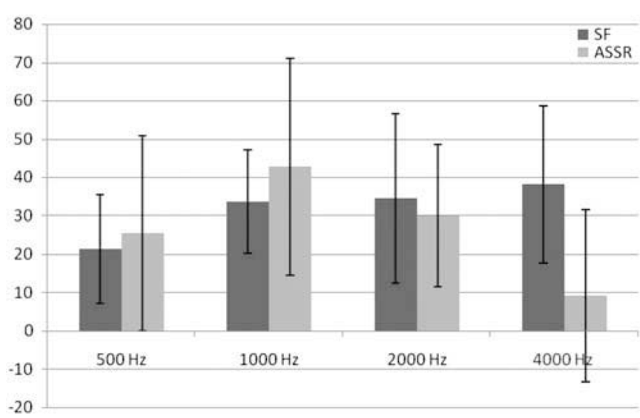
There has always been a need for objective tests that assess auditory function in infants, young children, and/or any patient whose development level precludes the use of behavioral audiometric techniques. Although the ABR

Figure 4



Correlation between sound field hearing test and free field ASSR test results (dB HL) at 2000 Hz among the aided patients. ASSR, auditory steady-state response; SF, sound field.

Figure 5



Functional gain (dB HL) as per sound field test compared with free field ASSR test results (dB HL). Note: error bars represent mean ± 1SD. ASSR, auditory steady-state response; SF, sound field.

Table 3 Comparison between the functional gain (dB HL) obtained using both sound field and free field auditory steady-state response tests at the different test frequencies

	SF test		ASSR test		
Frequencies (Hz)	Mean functional gain	SD functional gain	Mean functional gain	SD functional gain	*P* value
500	21.36	14.16	25.45	25.44	0.646
1000	33.64	13.43	42.73	28.32	0.352
2000	34.55	22.07	30.00	18.44	0.606
4000	38.18	20.53	9.09	24.68	0.007**

**Highly significant at $P \leq 0.01$.

is considered as the 'gold standard' in the field of objective audiometry, it has its own set of limitations. The ASSR has gained considerable attention and is considered as a promising addition to the AEP 'family' to address some of the limitations of the ABR. The ASSR promises to estimate all categories of hearing loss (mild to profound) in a frequency-specific manner. It also provides the possibility of validating HA fittings by determining the functional gain of HAs by determining unaided and aided ASSR thresholds [24].

On the basis of this rationale, the present study evaluated the ASSR-aided FF thresholds compared with behavioral SF-aided thresholds in adult patients in an attempt to assess the usefulness of ASSR in young children and infants and difficult-to-test individuals, who cannot provide reliable behavioral responses to either aided or unaided sounds. The results showed that the highest mean threshold difference was found at 500 Hz ($P = 0.01$) (Fig. 2). Furthermore, there was a positive correlation between the two tests at 1 and 2 kHz, where the correlation coefficient was (0.65 and 0.69) and the P value was (0.03 and 0.017) for both frequencies, respectively (Table 2 and Figs 3 and 4).

This is in agreement with Picton *et al.* [11], who reported that ASSR responses to amplitude-modulated tones with modulation frequencies between 80 and 105 Hz can be recorded when multiple stimuli are presented simultaneously through an SF speaker and amplified using an HA. Responses were recorded at carrier frequencies of 500, 1000, 2000, and 4000 Hz in a group of 35 hearing-impaired children using HAs. The physiologic responses were recorded at intensities close to the behavioral thresholds for sounds in the aided condition, with average differences between the physiologic and behavioral thresholds of 17, 13, 13, and 16 dB for carrier frequencies 500, 1000, 2000, and 4000 Hz. They concluded that the technique shows great potential as a way to assess aided thresholds objectively in patients who cannot reliably respond on behavioral testing and that this procedure seems more useful than procedures using transient stimuli. However, because ASSR cannot provide information on how well the nonlinear processing of the HA is benefiting the listener, it does not provide information on how the aided sound is perceived, following processing in the brain.

Stroebel [24] concluded that HAs appeared to transduce the ASSR-modulated tones with good fidelity; the spectral characteristics of the modulated tones played through an analog HA with no compression are well preserved. The fact that the stimuli are much more stable over time than brief transients means that they are more reliably transferred through the FF speakers and HAs, even when the HAs are nonlinear.

Functional gain is one of the most used procedures in the verification of the prescribed parameters of HAs. Several attempts have been made in order to reproduce the functional gain test through electrophysiological procedures [8]. In the present study, we measured functional gain using the FF ASSR objective electrophysiological test versus the behavioral SF test. The only difference between the two tests was found at 4000 Hz ($P = 0.007$) (Table 3, Fig. 5). This difference might be attributed to the electroacoustic characteristics of HAs. This indicates that the FF ASSR test could be used in difficult-to-test patients to assess HA performance with reliable results at 500, 1000, and 2000 Hz.

This is in agreement with the study of Stroebel *et al.* [25], who explored aided ASSR compared with unaided ASSR thresholds and subsequent behavioral thresholds in a group of six young infants with hearing loss who received HAs between 3 and 6 months of age. Aided ASSR thresholds were obtained in 83% of frequencies where aided behavioral thresholds were obtained, with a mean threshold difference of 13 ± 13 dB. The aided ASSR-based threshold estimates were within 15 dB of behavioral thresholds in 63% of cases, indicating a moderate correlation ($r = 0.55$). Comparison of aided and unaided ASSR measurements showed an average functional gain of 36 ± 15 dB. These results indicate that ASSRs can provide the first evidence of robust HA benefit in young infants several months before behavioral responses are observed.

Damarla and Manjula [26] examined the possible use of the ASSR technique in HA fitting. The relationship between the real ear insertion gain and ASSR gain (unaided ASSR threshold vs. aided ASSR threshold) was examined. Thirty adults with mild to moderately severe sensorineural hearing loss were assessed. ASSR gain and real ear insertion gain were highly correlated with significant values ($P < 0.05$). Paired-sample t-tests showed that there was no significant difference at all test frequencies. They concluded that the ASSR technique shows great potential in HA fitting for those who cannot reliably respond on behavioral testing.

Conclusion

From this study, the authors could conclude that SF audiometry and FF ASSR unaided and aided thresholds showed very similar results, and this indicates that ASSR may be a good alternative method for the measurement of hearing level in infants and children, for whom PTA is not possible. FF ASSR appears to be a reliable procedure for the verification of HA fitting and can be used to assess functional gain in difficult-to-test populations and children. We recommend future research on the effect of the electroacoustic characteristics of HAs on aided FF ASSR thresholds and using it in the adjustment of HAs or monitoring its performance.

Acknowledgements

Conflicts of interest

There are no conflicts of interest.

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