Single monotic auditory steady-state response in children with severe to profound sensorineural hearing loss

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Aim
The aim of the study was to find out the predictive value of single monotic auditory steady-state response (ASSR) in hearing threshold estimation in children with severe to profound sensorineural hearing loss (SNHL).

Materials and methods
Forty-eight children (96 ears) with severe to profound SNHL were included. They were subjected to age-based audiological evaluation. Single monotic ASSR was obtained and analyzed for all children using test signals of 250, 500, 1000, 2000, and 4000 Hz, modulated in either ears at high rates of 67, 74, 81, 88, and 95 Hz, respectively, using GSI Audera evoked potential system.

Results
The number and percentage of ASSR detected were highest at 1000, 500, and 2000 Hz, respectively in all children. The ASSR thresholds obtained were statistically correlated with the behavioral audiometric thresholds at the corresponding frequencies. A considerable number of ears with no sound field thresholds or click auditory brainstem response responses showed ASSR.

Conclusion
Single monotic ASSR, with high modulation frequencies, has shown to be a reasonable method for estimating hearing sensitivity in the mid-conventional audiometric frequencies in children with severe to profound SNHL.

Keywords:
auditory steady-state response in children, frequency-specific auditory evoked potential, sensorineural hearing loss

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Introduction

Auditory steady-state response (ASSR) audiometry is a commercially available tool used to predict behavioral auditory threshold. Its particular value stems from its ability to measure frequency-specific responses in the background electroencephalogram (EEG) to auditory stimuli presented across a broad range of frequencies and sound pressure levels [1].

Several attractive attributes have been reported in the clinical applications of ASSR. The test stimuli are reasonably frequency specific regardless of the mode of modulation. The steady tonal stimuli used in ASSR permit higher outputs to be realized than do the typical evoked response test systems. ASSR can provide threshold information at intensity levels of 120 dB and higher. This helps to differentiate between severe and profound categories of sensorineural hearing loss (SNHL) [2]. Multiple frequencies and/or two ears can be tested simultaneously. Finally, the spectrum of the response is predicted precisely without the need of subjective interpretation of the recorded response.

Hence, the common limitation of most clinical tests of auditory evoked potentials is overcome [3]. This uniquely qualifies the ASSR for investigation of residual hearing in young and difficult-to-test cochlear implant candidates [4].

ASSR was extensively studied in adults with severe to profound SNHL [1,5,6]. Many researchers recommended that ASSR results in adults could not be simply implemented in children [7]. Nevertheless, ASSR studies conducted on children with severe to profound SNHL are scarce. Accordingly, this study was designed to find out the predictive value of single monotic ASSR in hearing threshold estimation in children with severe to profound SNHL. The relationship between the behavioral hearing thresholds and the ASSR thresholds was explored in this group of children.

Materials and methods

Patients

A total number of 48 children (96 ears), collected from the Hearing & Speech Institute, were included in the present study. All children had severe to profound SNHL (hearing threshold ≥70 dB HL for octave frequencies 250–8000 Hz) and normal middle ear functions. Written informed consent was obtained from their parents. The research protocol was approved by the research ethics committee, Ain Shams University.

Procedures

All children were subjected to the following:

(1) Detailed history taking and otological examination.

(2) *Audiological evaluation*: This included tympanometry and acoustic reflex threshold measurements using Interacoustics AZ model AZ26 with 220 Hz probe tone, calibrated according to ANSI S3.39-1987. In sound-treated room model Amplisilence E, pure tone and speech audiometry were performed using the two-channel Audiometer Interacoustics model AC40 calibrated according to ANSI S.3.6, 1996 with headphones TDH 39 and bone vibrator B71. Age-based hearing threshold determination was performed as follows:

   (a) *Children above 3 years*: The method of threshold estimation, dependent on the child cooperation, was either conditioned play audiometry or voluntary thresholds [8].

   (b) *Children below 3 years or uncooperative children underwent the following:*

      (i) Behavioral observation audiometry (BOA) [8].

      (ii) *Auditory brainstem response (ABR)*: ABR was performed during sleep using the GSI Audera Grason-Stadler evoked potential system in a single-walled sound-treated room. The test procedures followed Sininger [9] protocol.

(3) ASSR:

Single monotic ASSR was tested for all children while sleeping using the two-channel GSI Audera evoked potential system. Two-channel recordings consisted of positive recording from Fpz, negative on both mastoids according to tested ear, and a ground on the forehead. The duration of testing for each child lasted 45 min.

The ASSR test stimuli were modulated pure tones presented through Grason-Stadler GSI TIP50 insert earphones with foam earplugs. The test protocol applied was the default test set for children aged less than 10 years. The test signals used were 250, 500, 1000, 2000, and 4000 Hz, modulated in both ears at high rates of 67, 74, 81, 88, and 95 Hz, respectively. High modulation rates ensure a satisfactory signal-to-noise ratio during sleep. Each signal is amplitude and frequency modulated and individually presented to either ear. An amplitude modulation depth of 100% and frequency modulation width of 10% of the carrier tone was used to maximize the response amplitude [10]. ASSRs were initially obtained at the maximum sound levels of 106 dB HL for the 250 Hz carrier, 120 dB HL for the 1000 Hz, 117 dB HL for the 2000 Hz, and 115 dB HL for the 500 and 4000 Hz carrier frequencies. To estimate the ASSR thresholds, the level of the stimulus was decreased in 10 dB steps until the response could no longer be detected. It was then increased in 5 dB steps until the response is detected. Once ASSR thresholds have been established over a number of frequencies, the software provided the option to extrapolate from these results the patient's estimated behavioral audiogram.

ASSR analysis was performed as described by Cohen *et al.* [10]. The presence or absence of a response was determined automatically with a statistical detection criterion based on phase coherence, which looked for nonrandom phase behavior at which the system calculated the probability that a set of observed phase angles could occur in the absence of a response. A test run was terminated either when the statistical criterion was reached (after a minimum of 16 samples) or after 64 samples if the criterion had not been reached.

The Audera system has three result options: (a) phase-locked result, when a significant response is found regardless of the noise level; (b) random result, when no response is found and the EEG does not exceed the noise threshold level; (c) noise result, when no response is found after 64 samples and when the EEG exceeds the noise threshold limit.

All collected data were statistically analyzed using IBM SPSS program (Statistical Package for Social Sciences) software version 18.0.

Results

The study group children (n = 48) comprised 25 boys (52.1%) and 23 girls (47.9%). Their mean age (mean ± SD) was 3.9 ± 1.9 years, with a range of 1.5–10 years. According to the age, all children were divided into two subgroups. Subgroup 1, at least 3 years age, included 28 children (n = 56 ears) with mean age of 4.9 ± 1.8 years. Subgroup 2, less than 3 years age, included 20 children (n = 40 ears) with mean age of 2.4 ± 0.8 years.

Results of subgroup 1: The pure tone audiometry (PTA) thresholds were in the severe to profound category of SNHL (Table 1, Fig. 1). The number of ears showing PTA threshold responses decreased with the increase in the tested frequency.

The ASSR detected in this subgroup was highest at 1000, 500, and 2000 Hz, respectively, and lowest at

4000 and 250 Hz (Fig. 2). Observing the mean ASSR thresholds, no statistically significant difference existed between the right and left ears (Table 2).

Notably, the ASSR thresholds obtained from subgroup 1 were statistically significantly higher than the behavioral PTA thresholds. The difference was calculated to be about 18.4 ± 7.7, 19 ± 6.7, 14.4 ± 8.7, 14.7 ± 8.8, and 15.5 ± 11 dB at 0.25, 0.5, 1, 2, and 4 kHz, respectively. A statistically significant correlation between PTA and ASSR thresholds was evident at 500, 1000, and 2000 Hz (Table 3, Figs 3–5).

Results of subgroup 2: The majority of children showed sound field responses only at lower frequencies. Around 75 and 85% of tested children did not show sound field responses at 2 and 4 kHz, respectively (Table 4). Click ABR was absent at 100 dBnHL in 90% of ears. Only three ears showed ABR response at 80 dBnHL and one ear at 90 dBnHL.

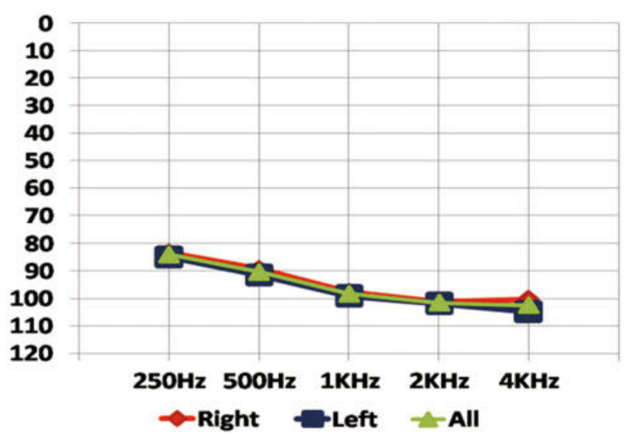
Table 1 Mean and SD of PTA thresholds in subgroup 1

Frequency (Hz)	Number of ears (n = 56)	Mean ± SD	Range (dB HL)
250	56	84.1 ± 7.0	70.0–100.0
500	56	90.4 ± 7.9	75.0–110.0
1000	54	98.4 ± 8.9	80.0–120.0
2000	47	101.6 ± 9.9	80.0–120.0
4000	36	102.5 ± 10.1	85.0–120.0

Table 2 Mean, SD, paired *t*-test, and *P* value of auditory steady-state response in subgroup 1

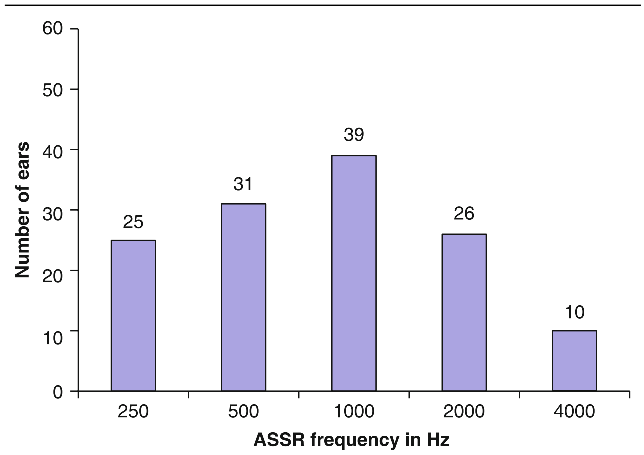
Frequency (Hz)	Right ear (mean ± SD)	Left ear (mean ± SD)	*t*-value	*P* value
250	100.44 ± 7.84	99.33 ± 6.98	0.517	0.619
500	106.09 ± 7.78	106.55 ± 6.46	0.171	0.867
1000	111.56 ± 6.25	109.06 ± 7.79	0.866	0.400
2000	113.43 ± 4.39	111.29 ± 6.60	0.685	0.519
4000	112.50 ± 3.54	102.50 ± 10.61	2.000	0.295

Figure 1



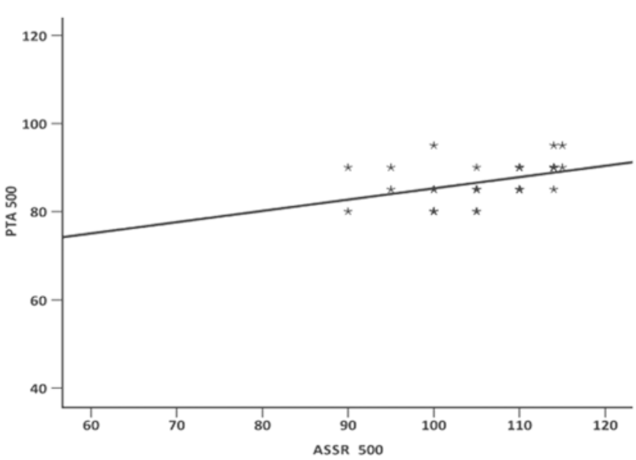
PTA thresholds in ears of subgroup 1.

Figure 2



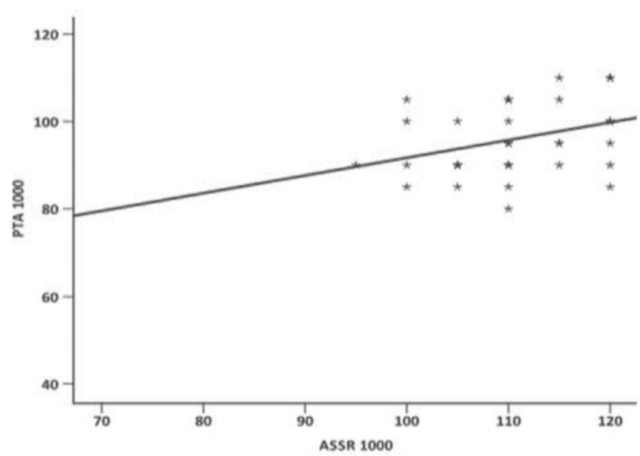
Auditory steady-state response (ASSR) response detection in ears of subgroup 1.

Figure 3



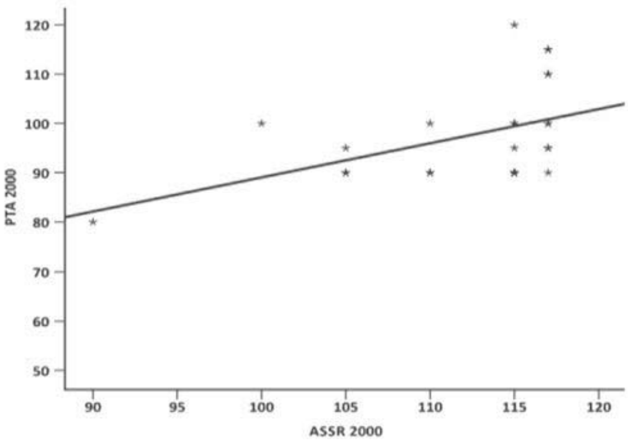
Scatter plot between PTA and auditory steady-state response (ASSR) at 500 Hz in subgroup 1.

Figure 4



Scatter plot between PTA and auditory steady-state response (ASSR) at 1000 Hz in subgroup 1.

Figure 5



Scatter plot between PTA and auditory steady-state response (ASSR) at 2000 Hz in subgroup 1.

Similar to subgroup 1, the ASSR detected was highest at 1000, 2000, and 500 Hz and lowest at 4000 and 250 Hz (Table 5). No statistically significant difference existed between the right and left ear results. The difference between the better ear sound field thresholds and ASSR reached up to 24.3 ± 9, 26.9 ± 8.5, 22.7 ± 4.6, 22.8 ± 11.1, and 23.3 ± 7.6 at 0.25, 0.5, 1, 2, and 4 kHz, respectively (Table 6).

Analysis of the ASSR in ears with no sound field response at different frequencies showed that ASSR was detected in 47% of ears at 2 kHz followed by 39% at 1 kHz, 27% at 4 kHz, and 8% at 500 Hz. No ASSR could be obtained at 250 Hz (Table 7). Moreover, in ears with no click ABR response, the ASSR was obtained in 53 and 25% at 2 and 4 kHz, respectively, at 112 dB HL.

Table 3 Pearson correlation coefficient '*r*' and *P* value between PTA and auditory steady-state response thresholds in subgroup 1

Hz	250	500	1000	2000	4000
N	25	31	39	25	9
r	0.312	0.413	0.348	0.474	−0.234
P	0.129	0.021*	0.030*	0.017*	0.545

*Significant.

Table 4 Sound field thresholds (better ear response) obtained from subgroup 2

Frequency (Hz)	*n* (%)	Mean ± SD	Range (dB HL)
250	14 (70)	73.9 ± 7.1	65.0–85.0
500	14 (70)	77.9 ± 6.4	65.0–85.0
1000	11 (55)	81.8 ± 4.6	70.0–85.0
2000	5 (25)	82.0 ± 6.7	70.0–85.0
4000	3 (15)	81.7 ± 5.8	75.0–85.0

Table 5 Results of auditory steady-state response in subgroup 2

Frequency (Hz)	Number of ears (*n* = 40) [*n* (%)]	Mean ± SD	Range (dB HL)
250	20 (50)	99.20 ± 7.54	80–106
500	23 (57.5)	105.39 ± 7.91	85–115
1000	27 (67.5)	109.63 ± 7.71	95–120
2000	23 (57.5)	108.43 ± 10.90	80–117
4000	13 (32.5)	107.15 ± 9.80	90–115

Table 6 Comparison between better ear auditory steady-state response and sound field thresholds in subgroup 2

Frequency (Hz)	*N*	ASSR (dB HL)	*N*	Sound field (dB HL)	*t*-value	*P* value
250	13	97.8 ± 7.3	13	73.5 ± 7.2	9.67	<0.001*
500	13	104.2 ± 7.3	13	77.3 ± 6.3	11.35	<0.001*
1000	11	106.4 ± 7.4	11	81.8 ± 4.6	11.84	<0.001*
2000	5	104.8 ± 13.8	5	82.0 ± 6.7	4.565	0.010*
4000	3	105.0 ± 13.2	3	81.7 ± 5.8	5.292	0.034*

ASSR, auditory steady-state response; *Significant.

Table 7 Auditory steady-state response in ears with no sound field response at different frequencies

Frequency (Hz)	Number of ears with ASSR [*n* (%)]	Number of ears with no ASSR [*n* (%)]
250	0 (0)	12 (100)
500	1 (8)	11 (92)
1000	7 (39)	11 (61)
2000	14 (47)	16 (53)
4000	9 (27)	25 (73)

ASSR, auditory steady-state response.

Discussion

A variation in ASSR response detection across frequencies was evident in the studied children. One of the explanations might be related to the maximum stimulation intensity across frequencies provided by the Audera equipment. It is the highest at 1 kHz (120 dB HL) and the lowest at 0.25 kHz (106 dB HL). The absence of the response at 4 kHz in a large number of children could be related to the severity of the hearing loss at this particular frequency.

This is in agreement with the study by Ahn *et al.* [11] who found that the largest percentage of absent ASSR was at 4 kHz (31.6%) in adult patients with severe to profound SNHL. In a study by Swanepoel *et al.* [12] on 15 children with severe to profound SNHL, the largest responses of ASSR obtained were at 2, 1, 4, and 0.5 kHz, respectively.

The difference between ASSR and PTA thresholds was greater at lower frequencies (0.25 and 0.5 kHz) compared with mid and higher frequencies. Van Maanen and Stapells [13] emphasized that the difference in thresholds between the behavioral measures and ASSR in children with severe to profound SNHL depends on the ASSR technique used. Using single monotic

ASSR, Ahn *et al.* (2007) found mean differences of 30, 18, 20, and 17 dB at 0.5, 1, 2, and 4 kHz, respectively. In contrast, lesser differences of 6 ± 10, 4 ± 8, 4 ± 9, and 4 ± 12 dB for frequencies 0.5, 1, 2, and 4 kHz were obtained by Swanepoel *et al.* [12] using dichotic single frequency ASSR.

The larger difference obtained, in this study, when using the single monotic ASSR (GSI Audera) may be related to the number of the harmonic overtones. The GSI Audera only takes into account the first overtone, whereas the other ASSR systems study phase and amplitude of a number of the harmonic overtones. When several overtones are studied, additional information can be gathered and more reliable ASSR thresholds can be obtained [5]. Another factor could be related to the sensitivity of GSI Audera to background interferences. These might lengthen the recording time up to 60 min per child [1].

The increased differences between sound field thresholds and ASSR in subgroup 2 was also related to the limits of loudspeaker (85 dBHL). This intensity limits missed children in the profound degree. On the other hand, the ASSR… in subgroup 2 provided a stimulation level up to 106–120 dB HL. This implied the importance of a technique such as the ASSR to provide threshold data for profoundly deaf children.

Despite these shortcomings, a single frequency ASSR per ear, used in this study, was suggested in children with severe to profound SNHL to eliminate the possible interactions between multiple stimuli when applied at high intensities. Intensity levels above 60 dB sound pressure level may contaminate the accuracy of responses [3].

Dimitrijevic *et al.* [14] stated that the closer ASSR to PTA using monotic single ASSR in profound hearing loss category can be attributed to the loudness recruitment and the limited dynamic range of residual hearing. However, in children with normal hearing, the mean ASSR thresholds were 42 ± 10, 35 ± 10, 32 ± 10, and 36 ± 9 dB HL for 0.5, 1, 2, and 4 kHz, respectively [7]. Compared with adults, these thresholds were elevated by an average 11 dB. Using multiple ASSR, the thresholds obtained were 36, 30, 24, and 15 dB HL at 500, 1000, 2000, and 4000 Hz, respectively [13].

The statistically significant correlation observed in subgroup 1 between PTA and ASSR thresholds (Table 3) is in agreement with the study by Ghannoum *et al.* [6]. They found that the best correlations between PTA and ASSR thresholds were present at 500 Hz, 1 kHz, 2 kHz, and 4 kHz in adults with severe SNHL. Similarly, Picton *et al.* [3] reported strong correlation between the behavioral and ASSR thresholds for 1000, 2000, and 4000 Hz.

The reduced correlation between ASSR and PTA at 4 kHz observed in the current study was reported by Dimitrijevic *et al.* [14], Swanepoel *et al.* [12], and Ahn *et al.* [11]. However, the explanation of such finding was not clear across studies.

Observing the ASSR at 250 and 500 Hz in this study, a higher difference existed between behavioral thresholds and estimated ASSR values with reduced correlation at 250 Hz. Similar findings were reported by Dimitrijevic *et al.* [14] and Luts and Wouters [7]. This was explained on the basis of neural synchrony. There is likely longer latency in the neurons responding to the low-frequency sounds caused by the broader region of activation on the basilar membrane. This decreases the time-locked summation of the responses.

Another explanation by Rance [4] stated that low-frequency stimuli (250 Hz) at high intensities might result in somatosensory rather than auditory responses. The problem in estimating ASSR thresholds at 250 Hz could result from the low-frequency evoked response, which has a greater intrinsic jitter due to neural asynchrony.

From the aforementioned discussion, it can be concluded that the hearing threshold detection at 250 Hz is still solely based on behavioral estimation (sound field testing in infants). The findings shown in this study supported the reliability of sound field testing at 250 Hz. In group 2, all ears (100%) with absent sound field response at 250 Hz had absent ASSR (Table 7). The importance of detecting PTA at 250 Hz stems from its role in hearing aid adjustment and subsequent response satisfaction.

The determination of profound SNHL in children is challenging. In subgroup 2, the percentage of children with residual hearing thresholds unmeasurable with sound field ranged from 30 to 85% at different frequencies. The responses to click ABR were only detected in 10% of this subgroup. Using single monotic ASSR, a considerable percentage of subgroup 2 ears showed ASSR responses particularly at 1, 2, and 4 kHz. Compared with click ABR, ASSR was obtained from 53 and 25% of children with absent ABR at 2 and 4 kHz, respectively.

This confirms that the absence of ABR and behavioral sound field stimulation thresholds does not rule out the presence of residual hearing. Similarly, a high percentage of ASSR detection in the absence of click

ABR was reported by Swanepoel *et al.* [12] with an average threshold at 110 dB HL. ASSR can be a primary source of information regarding profound levels of hearing loss. Studies conducted to compare ASSR and click ABR in infants and young children with milder degrees of SNHL indicated significant correlations between both techniques [7].

Finally, the average time for recording of the monotic single ASSR thresholds in this study ranged from 30 to 60 min for each child. This duration was needed for threshold estimation at five frequencies (0.25, 0.5, 1, 2, and 4 kHz) sequentially at varying intensities in each ear separately. The preparation of the patients, electrode placement, impedance checks, stabilization of test environment, and the time of sedation were not included in the calculations.

Roeser *et al.* [15] demonstrated that the measurement time can be shortened by up to 50%, if stimulation occurs in both ears simultaneously. Luts and Wouters [7] reported an average time of 50 min for Master and 44 min for GSI Audera. The long duration of ASSR testing limits its wide application, particularly in children.

Conclusion

The presence of ASSR thresholds at increased intensities not attainable with ABR and often not with behavioral measures in young children makes this technique uniquely suited to the evaluation of severe and profound SNHL. Single monotic ASSR, with high modulation frequencies, has proven to be a reasonable method for estimating hearing sensitivity in the mid-conventional audiometric frequencies. This can provide important information for use in the cochlear implant selection process, alerting clinicians to the possibility that an ear may have useful aided hearing.

ABR and ASSR each contribute importantly, and rather uniquely, to the pediatric audiologic test battery. The relationship between the two techniques is not competitive but rather complementary. The authors recommend that, for infants with severe to profound SNHL, sound field should be applied first for detection of low frequencies thresholds followed by ABR to click stimuli. If no response is obtained to click ABR, the examiner should proceed to ASSR testing at 500, 1000, and 2000 Hz. Furthermore, multiple dichotic stimulation should be investigated in children with severe to profound SNHL to minimize the duration of testing. The role of CE chirp stimulus in ASSR deserves to be studied to increase the response detection especially close to threshold.

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Conflicts of interest

There are no conflicts of interest.

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