Hearing Screening Using Auditory Steady State Responses Obtained by Simultaneous Air- and Bone-Conduction Stimuli

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Abstract
Introduction and objectives: Minimising false positives rates is an important goal of universal newborn hearing screening programmes. An adequate way for reaching that goal could be differentiating between transient conductive hearing losses (false positives) and permanent sensorineural hearing impairments (true positives) by means of a methodology that studies electrophysiological responses obtained using both air- and bone-conduction stimuli.

Our objective was to evaluate the efficiency of an automated hearing screening test based on auditory steady state responses obtained using simultaneous air- and bone-conduction stimuli. Methods: A sample of 80 high risk babies less than 2 months of born were screened using the automatic screening test. A confirmatory clinical and electrophysiological evaluation was used as the gold standard.

Results: The estimated diagnostic efficiency of this screening test was equivalent (100% sensitivity and 97.7% specificity) to the efficiency reported for otoacoustic emissions and automated auditory brainstem responses. The introduction of bone conduction in the screening reduced the false positive rate from 13.3% to 2.2%. The test duration was 5.3 (±1.9) min. In 34% of babies only one repetition of the test was needed to raising the result.

Conclusions: The screening test performed quite well in this initial clinical trial, differentiating transient conductive hearing losses from permanent neurosensory impairments and improving the diagnostic efficiency of auditory steady state responses.

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KEYWORDS
Hearing screening; Auditory steady state responses; Bone conduction; Simultaneous stimulation

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PALABRAS CLAVE
Cribado auditivo; Potenciales evocados auditivos de estado estable; Vía ósea; Estimulación simultánea

Cribado auditivo mediante potenciales evocados auditivos de estado estable obtenidos por estimulación simultánea de la vía aérea y la ósea

Resumen

Introducción y objetivos: Minimizar los falsos positivos constituye un objetivo de los programas de cribado auditivo universal. Una manera de lograrlo sería diferenciar entre los trastornos neurosensoriales (verdaderos positivos) y los conductivos transitorios (falsos positivos) mediante un método que permita estudiar la respuesta del sistema auditivo ante la estimulación tanto por vía aérea como por vía ósea.

El objetivo de este trabajo es evaluar: la eficiencia diagnóstica de una prueba automatizada de cribado basada en el registro de potenciales evocados auditivos de estado estable obtenidos por estimulación simultánea de vía aérea y vía ósea.

Métodos: Se estudiaron 80 bebés menores de 2 meses de edad. A todos se les realizó la prueba de cribado, siendo posteriormente citados para el estudio confirmatorio, cuyo resultado se consideró como criterio de verdad del estado audiológico del bebé.

Resultados: Con esta prueba se obtuvo una eficiencia diagnóstica equivalente (un 100% de sensibilidad y un 97,7% de especificidad) a la reportada para otras pruebas utilizadas en el cribado (emisiones otoacústicas y potenciales evocados de tronco cerebral), con la ventaja adicional de que la introducción de la vía ósea en el cribado permitió reducir la cifra de falsos positivos del 13,3 al 2,2%. La duración de la prueba fue de 5,3 (±1,9) min, siendo suficiente en el 34% de los casos una sola repetición para llegar al resultado.

Conclusiones: Esta prueba automatizada de cribado basada en el registro de potenciales evocados auditivos de estado estable permitió discriminar entre los trastornos conductivos transitorios y los neurosensoriales, reduciendo así los falsos positivos y elevando la eficiencia diagnóstica de esta metodología.

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Introduction

Brainstem auditory evoked potentials (BAEP) and otoacoustic emissions (OAE) by clicks constitute today’s automated equipment, used in hearing screening programmes.1-3 However, despite this equipment’s great accuracy and reliability,4-5 it has been demonstrated that to achieve a success rate of between 80% and 86% in the identification of congenital auditory disorders, the proportion of false positives ranges between 10% and 20%.4

These high false positive figures result in a considerable number of babies being unnecessarily referred for confirmatory diagnosis. This has a negative effect on the parents, with the high numbers of referrals raising the cost of the programme,6 and further complicates monitoring, with diagnostic services being overloaded to the detriment of those genuinely affected.

In order to reduce the number of referrals to manageable levels (between 1% and 5%), in the majority of universal hearing screening programmes, all babies who fail the test repeat it during their stay in the maternity ward, and the results of the OAE are confirmed with BAEP. This additional step reduces the probability of false positives and an overload of referrals, but consequently increases false negatives.7

Furthermore, considering that transient conductive hearing losses in newborns during the first 48 hours of life are a common problem8 and bearing in mind that they are a major source of false positives,9 a more appropriate strategy for reduction of false positive would be to identify the newborns with transient disorders due to problems in sound conduction and distinguish them from those with permanent neural damage of the receptor (sensorineural loss), the latter being the main objective of hearing screening.10 In order to do this, auditory sensitivity would need to be determined by both air conduction (AC) and bone conduction (BC) stimulation. In this case, when hearing by AC is affected but stimulation by BC remains normal we can infer that the disorder is conductive (false positives). On the other hand, if both canals are affected sensorineural involvement is probable (true positives).

At present there is no hearing screening equipment which uses bone stimulation conduction. The reason for this is that the techniques used for hearing screening involve rapid, transitory signals, provoked by very brief stimuli, and in this case determination of the electrophysiologi- cal threshold (ET) by BC has great limitations and artefact contamination.9

For hearing screening some authors have used auditory steady-state response (ASSR) obtained by air-conduction stimulation, showing the high efficacy of this methodology in early detection of hearing loss.11-12 Unlike other techniques used for hearing screening, the steady-state responses are continuous signals over time (as are the stimuli they provoke); this considerably reduces the contamination of the artefact registry and therefore enables reliable estimation of auditory sensitivity by BC.11,14
This study evaluates the diagnostic accuracy of an automated screening test based on the ASSR registries obtained by air and bone conduction stimulation and also introduces a new principle of stimulation (simultaneous air- and bone-conduction stimuli).

Material and Methods

Sample

We studied 80 babies with hearing loss risk factors. The babies were divided into 2 age groups. The first group comprised 44 newborns (84 ears) under 31 days old (19.7 ± 5.2 days), and the second group comprised 36 small infants (71 ears) aged between 31 and 60 days (38.8 ± 9.3 days). The Helsinki Declaration was taken into consideration for this study.

Screening Test

Screening was carried out using a software application designed for the Audix V device (Neuronic, Habana, SA). This application consisted of an automated recording and analysis test of ASSR obtained by AC and BC (Fig. 1). The test used the principle of simultaneous air and bone conduction stimuli as the methodology for stimulation of the auditory system, with the possibility of separate stimulation for each canal when deemed necessary by the evaluator. All stimulation and registry parameters were predefined, as were the criteria for screening termination.

Stimulation and Recording Parameters

Screening took place in physical premises, with low noise levels, in conditions of natural sleep. In all cases both ears were tested when possible. However, it was only possible to test one ear in 5 babies because they woke up and did not go back to sleep.

Fixed disk electrodes were placed (Ag/Cl), attached to the scalp with conductive paste, the area having been previously cleaned with alcohol. The active electrode was placed at Fpz (midline forehead), the reference electrode on the mastoid ipsilateral to the stimulated ear and the earth electrode on the contralateral mastoid. Prior to beginning the averaging, an automatic measurement of the electrode
impedance was taken; recording was not allowed to start if it exceeded 5 kΩ.

For simultaneous stimulation of both canals, the stimulus consisted of a combination of 2 continuous tones modulated in breadth, one bass (500 Hz) for the BC and the other treble (2000 Hz) for the AC, generating a modulation frequency of 107 and 111 Hz for the left ear, and of 104 and 115 Hz for the right ear. For individual stimulation of each canal these same tones were used separately, modulated at 115 Hz. The intensity of the stimulus was 50 dB HL for the AC, whilst the BC intensity was automatically selected depending on age (for the newborns it was 30 dB HL and for the small infants it was 35 dB HL).

The stimulus presentation was monaural. For the AC Ear Tone 3A insert phones were used, whilst for the BC the B71 vibrator was placed on the temporal bone with an elastic band which applied constant pressure.

Bioelectric activity was amplified with a gain of 100000 and analogically filtered between 10 and 300 Hz. For each potential between 8 and 20 recording windows were collected with 8192 samples each (digitised over a sample period of 1.37 ms). These were transformed into the frequency domain (using Fast Fourier Transform) and were subsequently averaged. Artefact rejection was carried out with shorter response window of 512 points whenever the activity exceeded ±50 μV.

Test Results

The detection of response was made using the T2H⁴⁹,⁵⁰ statistician. The test was automatically concluded when a significant response was obtained in 3 consecutive averagings (in both conductions for simultaneous stimulation, or in each separate canal for individual stimulation); or when a maximum of 20 averagings was obtained. Only responses obtained from the seventh averaging were considered.

Test results were automatically visible. For simultaneous stimulation, the result could be one of the following:

1. Pass: when a significant response was obtained in both canals.
2. Possible sensorineural loss: when there was no significant response in AC or BC.
3. Possible conductive loss: when a significant response was only obtained in BC, not in AC.
4. Failed, repeat: when no significant result was obtained in BC despite a significant AC response; or when there was no significant response in AC or BC due to high residual noise level.

For individual stimulation of each canal, the result could be "pass" or "fail", depending on whether there was a significant response in the canal used.

In all cases, we began the test with simultaneous stimulation of both canals (Fig. 2). If at first the result was "possible sensorineural loss", simultaneous stimulation was repeated once. If on the first or second attempt the test result was "possible conductive loss" the AC conduction was stimulated separately (a maximum of twice). Similarly, when the result was "Fail, repeat" due to failure only in the BC, the test was repeated individually (a maximum of twice).

However, if the result was "Fail, repeat" due to a high level of residual noise, the recording conditions were improved (cleaning, location of electrodes, infant’s condition) and the test was repeated.

We considered that the baby had not passed the screening when no result was obtained in either of the 2 canals (using simultaneous and/or separate stimulation).

Confirmatory Evaluation

All the babies were given a check-up at 3 months of age for confirmatory evaluation. A clinical-audiological assessment was made, which included an otoscopy, tympanometry and electrodiagnostic examination with a click-ASSR and BEAP. The result of this evaluation was used as the criterion of truth of the audiological condition of the baby.

Stimulation and Recording Parameters

All electrophysiological recording was carried out using Audix V equipment, in the same premises as the screening, with the babies in induced sedation with chloral hydrate (25 mg/kg weight). Positioning of the electrodes coincided with that used in the screening. The impedance was kept below 5 kΩ. Stimulus was monaural through TDH 49 headphones.

BEAP stimulus was one click lasting 0.1 ms at a frequency of 17 Hz. Bioelectric activity was amplified with a gain of 100000 and filtered between 100 and 2000 Hz. There were 2000 averagings with a window length of 15 ms.

For the ASSR we used a combination of 4 carrier tones (0.5, 1, 2, and 4 kHz) modulated in amplitude at 77, 85, 93 and 101 Hz for the left ear and at 81, 89, 97, and 105 Hz for the right ear. Bioelectric activity was amplified with a gain of 100000 and analogically filtered between 10 and 300 Hz. For each ASSR test between 16 and 32 windows were averaged, with 8192 points digitised to a sampling frequency of 730 Hz.

Auditory Brainstem Evoked Potentials Analysis

The BAEP were assessed by a neurophysiologist and the recordings considered normal had: typical morphology, absolute latencies and interpeak intervals within the normal range and presence of detectable V wave at 30 dB nHL.

T2H was used to detect response in the ASSR. Recordings were considered normal with significant response in the 4 frequencies explored at 30 dB HL. The HL average was calculated from the HLs obtained for 0.5, 1 and 2 kHz.

The level of severity of the loss was determined according to the HL obtained in both the BAEP and ASSR tests. Loss was classified as mild (35–50 dB HL), moderate (55–70 dB HL), severe (75–90 dB HL), or profound (above 90 dB HL).

Results

Most of the babies studied (96.3%) passed the hearing screening. Of these, a significant response was obtained in 142 ears for both canals, whilst for 10 ears (7 newborns) a significant response was only obtained for AC. Only
3 newborns (3.7%) failed the screening test, with suspected presence of a possible unilateral sensorineural loss. 45 of the babies had confirmatory check-ups (56.3% of the sample), and the existence of severe unilateral sensorineural deafness was confirmed in one of them. The other babies were diagnosed as having normal hearing.

To determine the diagnostic accuracy of the hearing screening only the results of those babies who completed the whole study (screening and confirmatory evaluation) were considered. Analysis of Table 1 shows that with this automated ASSR recording, sensitivity and specificity values of 100% and 97.7% respectively were obtained; there were 2.2% false positives.

If we analyse the efficacy of the test by only taking into consideration the ASSR results obtained by AC and not those of BC, as is the normal procedure in hearing screening, the rate of false positives in this case would rise to 13.3%, and the specificity of the test would drop to 86.5% (Table 2).

For the assessment of efficacy and reliability of a hearing screening test aspects other than diagnostic accuracy need to be considered. Fig. 3 shows the amount of times it was necessary to carry out simultaneous or individual stimulation of each canal to reach a conclusive result during screening. We may observe that in 40.6% of ears the result was obtained using simultaneous stimulation, without the need to complete the study with individual AC or BC stimulation. However, individual AC stimulation was performed in 31.6% of ears whilst in 27.7% AC had to be stimulated separately.

The duration of the test is another aspect to be taken into consideration when analysing a new screening methodology. On average, the duration of the complete test (including

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**Table 1** Diagnostic Accuracy of Automated Screening Based on ASSR Recording Using AC and BC Stimulation.

<table>
<thead>
<tr>
<th>Hearing screening</th>
<th>Audiological diagnosis</th>
<th>Total (ears)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Passed</td>
<td>Normal: 87 Positive: 0</td>
<td>87</td>
</tr>
<tr>
<td>Failed</td>
<td>Normal: 2 Positive: 1</td>
<td>3</td>
</tr>
<tr>
<td>Total</td>
<td>Normal: 89 Positive: 1</td>
<td>90</td>
</tr>
</tbody>
</table>

**Table 2** Diagnostic Accuracy of the ASSE Obtained by Air Conduction Stimulation.

<table>
<thead>
<tr>
<th>Hearing screening</th>
<th>Audiological diagnosis</th>
<th>Total (ears)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Passed</td>
<td>Normal: 77 Positive: 0</td>
<td>77</td>
</tr>
<tr>
<td>Failed</td>
<td>Normal: 12 Positive: 1</td>
<td>13</td>
</tr>
<tr>
<td>Total</td>
<td>Normal: 89 Positive: 1</td>
<td>90</td>
</tr>
</tbody>
</table>
repetitions which were necessary to achieve a result) was 5.3 (±1.9) min, with a minimum of 1.4 min and a maximum of 8 min per ear (Fig. 4).

**Discussion**

In this study we used ASSR methodology in an automated hearing screening test. Furthermore, a recording of the ASSR obtained by both AC and BC stimulation was introduced into the screening as a method to distinguish between transient conductive and sensorineural type disorders. As a result the rate of false positives was reduced, as were the number of unnecessary referrals, which helped to avoid parent anxiety and produced a more effective use of available diagnostic resources. Furthermore, a new principle of stimulation (simultaneous air-bone stimulation) was used to obtain stable state responses.

The diagnostic accuracy and reliability of the test used in this study was equivalent to or even higher than that reported for the normal techniques used for universal hearing screening (one click OAE and/or BAEP). Previous studies which analyse the diagnostic accuracy of different methods of hearing screening report 90%-95% sensitivity and 89%-91% specificity with OAE\(^3,21\) tests, whilst automated BAEP tests report higher rates of sensitivity and specificity (100% and 96%-98%, respectively).\(^3,4\) The lower diagnostic accuracy of the OAE compared with the BAEP tests is due to the fact that the former, using signals generated in the outer hair cells, does not enable the detection of lesions in the nerve or auditory canal, and are therefore normal in retrocochlear disorders such as auditory neuropathy, and are also of low diagnostic accuracy in the "at-risk" population which has the greatest concentration of auditory disorders.\(^5\) By contrast, the BAEP does evaluate lesions in the nerve and the auditory canal, and is therefore the method of choice for studying the "at-risk" population.\(^6\)

Other authors have used the ASSR results from AC stimulation for hearing screening.\(^10,12\) The complete auditory canal can be assessed with the ASSR. As a result, these tests offer the same as the BAEP which can detect auditory disorders in the whole population (with or without risk factors), whilst also offering the advantages of being more specific in frequency than the BAEP (they enable auditory losses at both high and low frequencies to be detected),\(^10,11\) and they are also more easily automated than the OAE and the BAEP.\(^19,20\) These authors report a 100% sensitivity and 92%-96%\(^10,12\) specificity with their use of the ASSR hearing screening, a lower result than that indicated in this study (97.7%) with its introduction of AC stimulation in the hearing screening. In fact, when we calculated the specificity of the test taking only the results of the test obtained by AC stimulation into consideration, its rate drops to 86.5%.

Besides diagnostic accuracy, this test had the additional advantage of identifying a possible transient conductive disorder in the 7 newborns (10 ears) who showed a response in the AC test but did not pass the BC test. This type of disorder heals spontaneously and for the purposes of hearing screening may be considered normal. Conductive losses are not, however, identifiable with current neonatal screening technology and are the cause of many false positives and unnecessary referrals.\(^2\) In this study, it would have been useful if conductive losses had been confirmed with impedanceometry in the hearing screening. However, although this was not performed, a complete audiological assessment was carried out on these 7 babies in the confirmatory evaluation whose hearing at 3 months of age was already normal. The temporary nature of the disorder was therefore confirmed.

Universal hearing screening is currently the objective of many screening programmes and its implementation implies assessment of all children at birth, prior to being discharged from the hospital. These newborns are assessed in spontaneous sleep and there is therefore not much time to perform the test. The technique used must therefore be applied rapidly. This automated test for recording ASSR was able to evaluate the hearing in each ear at an average of 5.3 (±1.9) min. Although these figures are adequate, they are higher than those previously reported on using ASSR for screening (2.6 [±1.6] min per ear)\(^12\); the duration is also higher than that reported for the OAE values (less than 2 min)\(^2,22\) and for the automated BAEP (1.5–5 min).\(^2,22–24\)

The increase in the screening duration found in this study with this automated test compared with other methods used to the same end can be explained if 2 aspects are taken into consideration. Firstly, we must consider the difficulties in obtaining records with a good sound-noise ratio in
newborns and small children, where responses are less comprehensive and there is much more artefact contamination of a biological nature (movements, dummy sucking) and non biological nature (electromagnetic interference), which impedes the process of extracting the response from the baseline noise which is measured by averaging. To resolve this problem the new methodologies18 that have been developed, aimed at dealing with artefact rejection and the extraction and detection of stable state responses in a more effective and faster manner, need to be included in this automated screening test.

Furthermore, the incorporation of AC stimulation in the screening probably also had an effect on the delay found in the duration of the test, since this led to the majority of babies (66%) needing to repeat the test, whether the stimulation was of both or individual canals. To reduce the amount of repetitions and consequently the duration of the test it is still necessary to perfect the procedure for location and adherence of the bone and air transducers. Minimum alterations to their design are required in order for this methodology to be used within the context of a universal hearing screening programme carried out in the maternity ward.

Conclusions

In this study, ASSR was used in an automated hearing screening test and a new stimulation principle was introduced to reduce the number of false positives. Diagnostic accuracy was raised with this methodology and unnecessary referrals for diagnostic confirmation reduced. Once it has been perfected this hearing screening based on recording ASSR obtained through AC and BC could represent a valid addition to current universal hearing screening protocols and be used in maternity wards.

Conflict of Interests

The authors have no conflict of interest to declare.

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