The Contribution of the Auditory Brainstem Responses to Bone-Conducted Stimuli in Newborn Hearing Screening

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Abstract
Both the auditory brainstem response (ABR) to air-conducted stimuli and evoked otoacoustic emissions have been questioned for their lack of specificity for permanent sensorineural hearing loss during the newborn period. Unfortunately, prevailing indices for detecting middle ear dysfunction such as otoscopy and tympanometry have not demonstrated adequate success to serve as a second line of screening during this time. The use of ABR to bone-conducted stimuli during the newborn period to differentiate sensorineural from conductive auditory deficits and thereby improving the efficiency of screening methods is advocated herein. Specifically a two-staged approach for the universal hearing screening of newborns prior to hospital discharge is suggested. The utilization of the ABR to air-conducted tonal stimuli (i.e., 500 and 2000 Hz) as a first line of testing is offered. Infants who display an identifiable and replicable ABR wave V to 30 dB nHL air-conducted tonal stimuli with a latency within plus two standard deviations of the mean of the age appropriate normative data in both ears are considered a "pass." For those infants that "fail" the initial hearing screening test, the employment of bone-conducted tonal stimuli is recommended. The purpose of this article is to summarize procedures associated with the implementation of ABR to bone-conducted stimuli with controlled signal delivery in the audiological screening/assessment of young infants.

Key words: ABR to bone-conducted stimuli, newborn hearing screening

It is generally accepted that the purpose of any screening protocol is to identify those individuals who have a greater probability of having a disease or pathology in order that they may be referred for further diagnostic evaluation (American Speech-Language-Hearing Association, 1995, 1997; Jacobson, 1990). Further, the choice of a screening test should be based on its ease of administration, comfort to the individual, cost effectiveness, and be short in duration. In addition, the test must demonstrate satisfactory test operating characteristics (i.e., be sensitive and specific). Both the purpose and choice of a newborn hearing screening protocol is identifying hearing impairment at birth in order to facilitate the necessary habilitation in a timely manner. To achieve this goal, current models recommend the screening of all newborns (American Speech-Language-Hearing Association, 1997; National Institute of Health, 1993). Both the auditory brainstem response (ABR) and otoacoustic emissions (OAEs) have been recommended (American Speech-Language-Hearing Association,
both serous and suppurative exudate (Buch & Jorgensen, 1964; deSa, McLellan et al., 1964; McLellan, Strong, Johnson, & Dett, 1962; Paparella et al.). Clinical studies have also reported the presence of exudate (Balkany, Berman, Simmons, & Jafek, 1978; Berman, Balkany, & Simmons, 1978; Jaffe, Hurtado, & Hurtado, 1970; McLellan, Strong, Vautier, & Blair, 1967; Stauth, Peloton, & Kiehn, 1976; Wren & Stool, 1971).

Unfortunately, prevailing indices for detecting middle ear dysfunction have not demonstrated adequate success to serve as a second line of screening during the newborn period. That is, otoscopy is difficult (Berman et al., 1978; Groszhus, 1982; Schröder & Kissling, 1981) and tympanometry employing a low-frequency probe tone is unreliable (Hinellfarb, Popolka, & Shanon, 1979; Holte, Margolis, & Cavaughan, 1991; Paradies, Smith, & Stuen, 1976; Schlegel & Schwartz, 1978; Spencer, Wiley, & Goldstein, 1985). Higher probe tone frequency tympanometry (McKinley, Crosse, & Reath, 1997) and wide band reflectance measures (Keefe, Bolen, Arehart, & Burns, 1995; Keefe & Levy, 1996) may prove to be more effective. What remains is the challenge to improve the specificity of screening methods employing air-conducted stimuli. In other words, how does one distinguish between ABR abnormalities due to permanent sensorineural hearing loss and conductive pathology as a consequence of transient middle ear dysfunction during the newborn period?

Bone-conducted stimuli delivery in conjunction with air-conducted stimuli delivery, a third means employed to differentiate sensorineural and conductive pathologies has been under-implemented in the clinical assessment of newborn hearing status. This practice stands in the face of more than 20 years of accumulated research data has demonstrated that ABR to bone-conducted stimuli is a reliable test measure (Cone-Wesson, 1995; Cone-Wesson & Ramirez, 1997; Cornacchia, Martini & Moro, 1983; Fos & Stapells, 1993; Gorga, Kaminis, Bouchaine & Bergman, 1995; Heik, 1980; Hooks & Weber, 1984; Muchitch, Newman & Hillesheimmer 1995; Nousaski & Stapells, 1992; Stapells, 1989; Stapells, & Gates, 1997; Stapells & Ruben, 1989; Stauth & Yang, 1994; Stauth, Yang & Stensrud, 1990; Stauth, Yang, Stensrud & Reinhold, 1993; Tucci, Raub & Latshaw, 1980; Warren, 1989; Weber, 1983; Yang, Ruptur, & Mousagian, 1987; Yang & Steuer, 1994; Yang, Steurer, Mirnay, & Vincen, 1993; Yang, Sturr, Stensrud & Holter, 1991; Yasuda & Cone-Wesson, 1987). The use of ABR to bone-conducted stimuli during the newborn period has been advocated for differentiating sensorineural from conductive auditory deficits and thereby improving the efficiency of
ABRs to bone-conducted stimuli in newborn screening

stimuli, however, attention must be given to a number of fac­tences between newborns and adults and pay particular attention to controlled signal delivery. The purpose of this article is to summarize procedures associated with the implementation of ABR to bone-conducted stimuli and controlled signal delivery in the audiological screening/assessment of young infants.

Anatomical Differences in Cranial Structure Between Neonates And Adults

The newborn and adult crania differ vastly. An understand­ing of these differences facilitates an appreciation for the need for controlled bone-conducted stimulus delivery during the newborn period. To begin with, the temporal bone articulates with four other cranial bones, that is, the occipital, parietal, sphenoid, and zygomatic. In the adult, as well as older infants and children, these bones are tightly sutured (Bast & Anson, 1944) and bone-conducted vibratory stimuli drive the cranium as a whole. This is not the case with the neonatal cranium. Membranous sutures separate the temporal bone of neonates from surrounding cranial bones (Crelin, 1973; Pierce, Mainen, & Bosma, 1978). Further, at gestational term the temporal bone consists of three unfused components namely the petrosal, squamosal, and annulus (Pierce et al.). Whereas the petrosal and squamosal communicate by bony approxi­mation along the petro-squamosal suture (Pierce et al.) the squamosal and petrosal articulate with the parietal and occipital bone by the membranous squamoso-petral and petro-oc­cipital sutures, respectively (Anson, Bast, & Richards, 1955; Bast & Anson, 1944; Crelin). The mastoid is formed at birth but the mastoid process is essentially devoid. The relative size of the newborn temporal bone is approximately one-half to one-third that of an adult. Housed in the petrosal are the membranous and bony labyrinth of the cochlea. The two labyrinths are adult size at birth (Crelin; Wong, 1983). As the petrosal is basically adult size and does not develop signifi­cantly post-parturionally, the cochlea occupies a relatively larger area of the temporal bone in the neonate than the adult does (Crelin; Wong).

It has been suggested that the effective intensity of a bone-conducted signal, if delivered from a posterior auricular bone-conductor placement, is greater in neonates than in adults (Foss & Stoppel, 1993; Stuart et al., 1990; Stuart, Yang & Green, 1994). In a posterior placement the bone vibrator rests medial to the auricle adjacent to its attachment to the skull such that the inferior longitudinal margin of the bone vibra­tor is parallel to a horizontal line drawn from the center of the entrance to the external auditory meatus. The posterior place­ment is believed to deliver more effective stimulus output to the temporal area of the temporal bone. As the placement of the bone vibrator moves from the posterior through a supero­posterior to a superior position effective stimulus delivery decreases as vibratory energy is disseminated through sur­rounding membranous sutures resulting in an attenuated sig­nal reaching the cochlea. Placement of the bone vibrator on other cranial bones (e.g., frontal or occipital bones) results in further attenuation of vibratory energy (Yang et al., 1987). For this reason, it has been estimated that the interaural at­tenuation of a bone-conducted click is approximately 25 to 35 dB for the neonate and 15 to 25 dB for the one-year old infant (Yang et al.). In clinical testing of ABRs to bone-con­ducted stimuli, masking of the contralateral ear is recommended. When evaluating neonates, masking of the non-test ear may be required at higher stimulus levels, for example, at 35 dB nHL (Yang et al.). Hence, the masking of non-test ear is of less concern when testing neonates with bone-conducted stimulation.

Delivery of Bone-Conducted Stimuli

Click generated by 100 µs rectangular voltage pulses and delivered through a bone vibrator (Radioear B70B) can be used to evoke ABR (Yang et al., 1987). Click stimuli presented at a fast rate such as 577/s with alternating polarity are recom­mended. For frequency specific stimulation, Stapells and colleagues (1989) have suggested the use of bone-conducted tonal stimuli for the assessment of newborns and young infants. ABRs to bone-conducted tonal stimuli show good frequency and place specificity particularly at low stimulus levels (Kramer, 1992; Nousak & Stoppel). Linearly gated tones with 2:1 rise-fall cycles with alternating onset polarity are recom­
V latency are observed for at low level stimulus intensities (Stuart, 1990).

For controlled bone-conducted stimulus delivery, a fine nylon line is attached under the skin, and then looped and tied around the transducer end adjacent to the proximal end of the vibrator. An elastic band with Velcro attached to the opposite ends is used to hold the vibrator in place. The elastic band is adjusted to maintain a vibrator-to-head coupling force of 425 ± 25 g. The elastic band is then positioned around the infant's head under the loop of nylon fishing line and against the bone vibrator. A spring scale (e.g., Ohaus Model 9014; available at most scientific supply companies) is attached to the fishing line and the vibrator is then manually pulled away from the scalp. Coupling force is measured at the point when the vibrator clears and becomes flush with the scalp (Yang & Stuart, 1990).

Recording Paradigm

For screening applications at lower stimulus levels an ipsilateral (i.e., noninverting electrode located at the vertex or high forehead) montage or vertical montage (i.e., with the inverting electrode located on the nape of the neck) is recommended (Stuart, Yang, & Botea, 1994). Yang, Stuart, and colleagues have employed the ipsilateral montage, consisting of three gold-plated cup electrodes including one attached to the high forehead (F), one attached to the inferior contralateral postauricular area (M), and one (common) attached to the high forehead (Yang, Botea, & Weber, 1984) is likewise not supported. Although vibrator placement may be controlled, means

Reliable ABRs to bone-conducted stimuli in newborn screening with a progressive increase in the high-pass filter cutoff (Stuart & Yang, 1994). The most pronounced effect is a statistically significant reduction in wave V amplitude. Compared to a 30 Hz high-pass filter cutoff, 40 to 50% reductions in wave V are experienced with high-pass cutoff frequencies of 100 and 150 Hz respectively for bone-conducted stimuli. The consequence of increasing the high-pass filter is a pronounced loss of the "slow" component of the ABR, which contributes largely to the spectral content of wave V (Kavanaugh, Dormeo, Franks, & Jin-Cheng, 1988; Laski & Mair, 1981).

Essential Considerations in Bone-Conducted Signal Delivery

Factors that may affect the ability of the ABR waveform to detect small changes in high-pass analog filtering. That is, statistically significant reductions in wave V amplitude and decreases in wave V latency are observed for at low level stimulus intensities.
to verify vibrator to head coupling force with these techniques
are not readily available.

Interpretation of Test Results

In the analyses of results of ABR to bone-conducted click stimuli, an abnormal finding is defined when the ABR elicited at 30 dB nHL does not show an identifiable and replicable wave V with a latency within plus two standard deviations of the mean of the age-appropriate normative data (Yang et al., 1993). Examples of age-appropriate reference values are displayed in Table 1. The degrees of auditory deficits during the newborn period have been classified as mild-to-moderate or severe-to-profound. Mild-to-moderate deficits are defined in ears which exhibited an identifiable and replicable ABR wave V at 30, 45, or 60 dB nHL with a latency exceeding normal limits or an identifiable and replicable ABR wave V at 45 and/or 60 dB nHL, but not at 30 dB nHL. (i.e., the ABR threshold was equal to or better than 60 dB nHL). Severe-to-profound deficits are defined in ears which an ABR wave V at 60 dB nHL cannot be identified (i.e., the ABR threshold was worse than 60 dB nHL). Furthermore, based on the contrast of ABR findings between air- and bone-conducted stimuli (i.e., air-bone gap), the types of auditory deficits are classified as sensorineural, conductive, or mixed. Ears that exhibited severe-to-profound deficits with no detectable ABR to bone-conducted stimuli at the output limitation of the bone vibrator (approximately 45 to 50 dB nHL) are classified as severe-to-profound sensorineural deficits.

It is recognized, however, that due to the limited dynamic range of the bone-conducted click stimuli, a conductive component cannot be ruled out in these cases.

### Table 1. Normal ABR Wave V Latency (ms), Standard Deviation, and Upper Limit

<table>
<thead>
<tr>
<th>Age Level</th>
<th>Mean</th>
<th>Standard Deviation</th>
<th>Upper Limit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Neonate</td>
<td>8.67</td>
<td>0.43</td>
<td>9.53</td>
</tr>
<tr>
<td>Four Mont.</td>
<td>7.76</td>
<td>0.33</td>
<td>8.42</td>
</tr>
<tr>
<td>One Yr.</td>
<td>7.44</td>
<td>0.23</td>
<td>7.92</td>
</tr>
<tr>
<td>Adult</td>
<td>7.56</td>
<td>0.28</td>
<td>8.26</td>
</tr>
</tbody>
</table>

Although ABRs to bone-conducted ronal stimuli have shown a good correspondence between normal cochlear sensitivity in infants with a diversity of external and middle ear pathologies (e.g., Gravel, Karstenberg, Stappells, Vaughan, & Wallace, 1989; Pierson, DeSouza-Smith, & Moran, 1994; Stappells & Ruben, 1989) there has yet to be a definitive study on how well ABR test results correspond to behavioral thresholds to bone-conducted ronal stimuli. Toward this realization, there remains no definitive suggestion as to how to interpret ABR test results to bone-conducted ronal stimuli during the newborn period.

### Newborn Versus Adult Differences in ABRs To Bone-Conducted Stimuli

Wave V latencies of ABRs to air-conducted click stimuli have been reported to be shorter than from bone-conducted stimuli at comparable stimulus intensity levels (Mauldin & Jung, 1979; Weber, 1983; Yang et al., 1987). With newborn infants Wave V latencies have been reported to be similar with air- and bone-conducted click stimuli at comparable stimulus intensity levels (Stuart et al., 1990, 1993, 1994; Yang et al., 1987, 1991). It is possible, however, that by manipulating controlled signal delivery either through changes in coupling force or bone vibrator placement the effective stimulus intensity delivered to the cochlea may be changed (Stuart et al., 1990, 1994; Yang et al., 1987, 1991). That being the case, the relationship of wave V latencies to air- and bone-conducted stimuli may be revealed to be shorter, longer, or equivalent in equimeters.

Newborn ABR thresholds to bone-conducted clicks appear to be better than adults' ABR thresholds if adult psychophysical thresholds are used as a reference (Cone-Wesson & Ramirez, 1997; Foxe & Stappells, 1993; Nousak & Stappells, 1992; Stuart et al., 1994). Infants display better thresholds to 500 Hz bone-conducted ronal stimuli than adults but the reverse is true for 2000 Hz bone-conducted ronal stimuli (Foxe & Stappells; Stappells & Ruben, 1989). There is a high correlation between ABR threshold estimates and pure tone thresholds for bone-conducted signals. ABR measures to bone-conducted clicks and ronal stimuli tend, however, to underestimate pure tone thresholds (Cone-Wesson, 1995; Stappells & Ruben).

### Clinical Implications for Newborn Hearing Screening and Conclusions

The ABR to bone-conducted stimuli has proven to be a feasible and reliable means for the identification of congenital sensorineural deficits in newborns (Cone-Wesson & Yamirez, 1997; Hooks & Wechs, 1984; Nousak & Stappells, 1992; Stappells & Ruben, 1989; Yang & Stuart, 1990, 1993). When one attends to stimulus delivery control reliable results can be expected (Yang, Stappells, & Green, 1988; Cone-Wesson & Ramirez, 1997).
It is suggested that the ABR to bone-conducted stimuli be viewed as a valuable addition in the assessment of cochlear reserve in infants who fail newborn auditory screening to air-conducted stimuli.

Specifically, a two-staged approach is recommended for the universal hearing screening of newborns prior to hospital discharge. The use of the ABR to air-conducted stimuli (i.e., 500 and 2000 Hz) is suggested as a first-line of testing. Infants who display an untestable and repeatable ABR wave V to 30 dB nHL, air-conducted to stimuli with a latency within plus two standard deviations of the mean of the age-appropriate normative data in both ears are considered a "pass". These infants may be discharged from the screening program if they do not exhibit any risk factor for hearing impairment. For those infants who fail the initial hearing screening test to air-conducted stimuli, the employment of bone-conducted total stimuli is advocated (i.e., 500 and 2000 Hz) as a means of preventing first-line failures from encumbering follow-up testing diagnostic evaluation. This is, neonates who fail the initial hearing need be rescanned by ABR to bone-conducted total stimuli in an effort to differentiate permanent sensorineural hearing loss from conductive pathology as a consequence of transient middle ear dysfunction prior to hospital discharge. Infants who fail the second line of ABR screening with bone-conducted total stimuli need be referred for a diagnostic evaluation. Implementation of the follow-up diagnostic evaluation is necessary to verify the existence of and to determine the severity of any hearing impairment in an effort to initiate any habilitative program for the infant. Ideally those referred from screening should receive diagnostic confirmation of auditory status within one month but not later than three months of discharge (American Speech-Language-Hearing Association, 1997). For those infants who fail the initial hearing screening test to air-conducted stimuli but pass the second line of ABR screening with bone-conducted total stimuli a rescreen with an ABR test to air-conducted total stimuli within one month but not later than three months of discharge is recommended. An abnormal finding at the second hearing screening is considered a valuable addition in the assessment of cochlear reserve in infants who fail newborn auditory screening.

Advantages of utilizing ABR to bone-conducted stimuli are self-evident. First, it allows clinicians to differentiate sensorineural from conductive defects in neonates who fail an ABR screening using air-conducted stimuli. Second, the timing of identification of substantial sensorineural defects can be advanced to the earliest stage of life. Finally, immediately following the assessment with ABR to bone-conducted stimuli, it may be psychologically less stressful for parents to be provided with more audiological information than to wait for follow-up testing months later.

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