**EFFECTIVE MASKING LEVELS FOR BONE-CONDUCTION AUDITORY
BRAINSTEM RESPONSE STIMULI IN INFANTS AND ADULTS WITH NORMAL
HEARING**

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Abstract

Background: Early hearing detection and intervention programs aim to limit delays in identifying ear-specific type/degree of hearing loss in infants using the auditory brainstem response (ABR). Ear-specific assessment poses challenges as sound delivered to one ear can travel across the skull and activate the contralateral cochlea. Wave V amplitude and latency measures ipsilateral and contralateral to the bone oscillator can be compared to isolate the test cochlea (AC testing also when large asymmetries are present). However, when comparison of ipsilateral/contralateral responses cannot isolate the responding cochlea, clinical masking is required. Effective masking levels (EMLs) for bone-conduction ABR testing in infants and adults have not been measured directly. This study aims to determine EMLs for 500- and 2000-Hz BC stimuli for normal-hearing infants (0-18 months) and adults.

Method: Participants were 10-13 adults and 13-15 infants with normal hearing. BC 500- and 2000-Hz tone pip stimuli at intensities approximating normal levels (Infants: 20 and 30 dBnHL at 500 and 2000 Hz, respectively; Adults: 500 and 2000 Hz at 20 and 30 dBnHL) were presented via a B-71 oscillator. White-noise masking was presented binaurally via ER-3A earphones (22-82 dBSPL; 10-dB steps). The lowest level of masking to eliminate a BC response was deemed the EML.

Results: For stimuli presented at 20 dBnHL, adult mean(1SD) EMLs for 500 and 2000 Hz were 65(9) and 53(6) dBSPL, respectively. Mean EMLs for infants were 80(6) dBSPL for 500 Hz at 20 dBnHL and 64(9) dBSPL for 2000 Hz at 30 dBnHL. Compared to adults, infants required

approximately 13 dB more masking at 500 Hz but a similar amount of masking at 2000 Hz.

Infants required 26 dB more masking at 500 versus 2000 Hz, whereas, adults required only 12 dB more masking at 500 versus 2000 Hz.

Conclusion: Maximum binaural effective masking levels for infant BC responses are as follows:

82 dBSPL for 20 dBnHL at 500 Hz; 72 and 82 dBSPL for 30 and 40 dBnHL, respectively, at 2000 Hz. Unsafe levels of white noise would be needed to effectively mask at greater stimulus levels.

Lay Summary

Early screening and intervention for hearing loss in infants play a critical role in their language development. When an infant does not pass a hearing screening, they are referred to an audiologist for a full hearing assessment using a test called the auditory brainstem response. During this test, it is important to test each ear separately, as sounds presented to one ear can travel across the head and enter the other ear, making it difficult to observe which ear is responding to the stimulus. A solution is to put white noise into the ear the audiologist is not testing at that moment. The present study determined the amount of white noise required to test each ear separately. This helps ensure that hearing test results are accurate so that audiologists can determine appropriate intervention.

Preface

The research described in this thesis was carried out in collaboration with my supervisor, Dr. Susan Small at the University of British Columbia. The study was originally conceived by Dr. Small, and I carried out participant recruitment, experiment set-up and execution, data analysis, and writing. Dr. Small assisted on all aspects of the study's development, including participant recruitment, study design, experiment set-up, statistical analysis, and writing.

This study was approved by the UBC Clinical Research Ethics Board (CREB), titled as “Effective Masking Levels for Bone-Conduction Auditory Brainstem Response Stimuli in Infants and Adults with Normal Hearing”; UBC CREB number: H16-01101.

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List of Abbreviations

ABR – auditory brainstem response

AC – air-conduction; air-conducted

ANSI -- American Nation Standards Institute

ANOVA – analysis of variance

ASHA – American Speech-Language-Hearing Association

BC – bone-conduction; bone-conducted

BCEHP – British Columbia Early Hearing Program

dB -- decibel

dB nHL – decibels normal hearing level

dB SPL – decibels sound pressure level

EEG -- electroencephalogram

EHDI – Early Hearing Detection and Intervention

EML – effective masking level

Hz – hertz

IA – interaural attenuation

μ N -- micronewton

μ V – microvolt

ms -- millisecond

OIHP – Ontario Infant Hearing Program

RETSPL – reference equivalent threshold sound pressure level

SD – standard deviation

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Chapter 1: Introduction

1.1 Introduction

With the realization that adequate hearing sensitivity is crucial for normal language and psychosocial development, standardized early hearing detection and intervention (EHDI) programs have been established to address the need to identify hearing loss early (Canadian Infant Hearing Task Force, 2016). Such programs aim to provide screening and diagnosis of hearing loss, as well as intervention to overcome the effects of hearing loss. Guidelines associated with such programs originate from the Yoshinaga-Itano research team, where they found that children whose hearing loss was identified by the age of six months were not only able to develop better language skills than peers diagnosed later but were also able to perform close to their normal-hearing age-matched peers (Yoshinaga-Itano, Sedey, Coulter & Mehl, 1998). Speech intelligibility is also affected. Audibility of high frequencies important for speech perception is important as well, to the extent that children with hearing loss may not be able to as adequately self-monitor their speech as children with normal hearing, and likewise for children who are fitted with hearing aids later. The result is a reduction in speech intelligibility the longer a child is not accessing higher frequencies required for speech perception (Stelmachowicz, Pittman, Hoover, Lewis & Moeller, 2004). Language development is not the only problem associated with hearing loss in children. There is evidence from school-age children that suggests a likelihood of negative consequences on a child's academic and social performance, as well as the child's self-esteem (Yoshinaga-Itano & Gravel, 2001). Additionally, parental stress is reduced when the hearing loss is treated, leading to the prospect of improved personal-social development in children during this pre-linguistic phase.

In Canada, the province of British Columbia has implemented an EHDI program (Canadian Infant Hearing Task Force, 2014). The goals of this program are to screen by one month of age, diagnose and identify hearing loss by three months of age, and provide early intervention and communication support by six months of age (BCEHP, 2012). This program encompasses the universal newborn hearing screening program, where the goal is to screen all newborns for hearing loss. When a child does not pass the screening, a diagnostic audiologic assessment follows, which includes an auditory brainstem response (ABR) assessment. The current study aims to further improve the accuracy of the ABR assessment in scenarios where a phenomenon called masking is required; this will be further discussed in later sections. Although visual reinforcement audiometry is commonly used to assess older infants and toddlers, the frequency-specific ABR is considered to be the method of choice for assessing hearing sensitivity for infants younger than six months of age, because they do not produce reliable head turns to sound (Moore, Wilson & Thompson, 1977; BCEHP, 2012).

The ABR is an auditory evoked potential recorded from electrodes placed on mastoids and on the forehead, and it is used to determine hearing sensitivity up to the level of the brainstem by having the clinician interpret the resulting waveforms (Fuxe & Stapells, 1993). Wave V is a clinically relevant landmark and its latency and amplitude can aid the interpretation of whether or not the child can detect a stimulus, at a certain level, up to, at least, the level of the brainstem. This interpretation requires both subjective and objective information. Objective information includes signal-to-noise ratio and residual noise measures, whereas subjective information includes determining the replicability of a waveform as well as identifying the latency and presence of peaks of certain waves. Together, the clinician is to make an overall impression on the presence of a peak, and thus, determine the presence of a response. The end

goal is to determine either the presence or absence of a wave V for a series of bracketed presentation levels to establish threshold. These thresholds are then converted from normal hearing levels (dB nHL) to equivalent hearing levels to predict behavioural hearing thresholds (Elberling & Don, 1987; Stapells, Picton, Durieux-Smith, Edwards & Moran, 1990). Details regarding neurogenerators of the ABR will be discussed in a later section.

Bone-conduction (BC) testing is a method by which an auditory stimulus is presented as a vibration of the skull to bypass the middle ear and stimulate the cochlea directly. Along with air-conduction (AC) hearing sensitivity, BC levels can determine the nature of the hearing loss, be it conductive, sensorineural, or mixed. British Columbia Early Hearing Program (BCEHP) protocols mandate that 2000 and 500 Hz be assessed first using the ABR, and in each case, BC is done when AC results are elevated, especially for 2000 Hz (Stapells, 2002; BCEHP, 2012). This would provide the minimal information required for intervention to proceed. Specifically in infants, wave V amplitude and latency differences in 2-channel BC ABR recordings are observed to help isolate the test ear. There can be cases where these differences are not as easily discernible as expected. As a result, it is not clear which cochleae are being stimulated and accurate ear-specific BC results cannot be obtained. The current study aims to overcome this issue.

In conventional pure-tone audiometry, masking is required to isolate the test ear from the non-test ear when there is an air-bone threshold gap of greater than 10 dB. That is, a narrowband masker stimulus is presented to the non-test ear, while the frequency-specific tone is presented to the test ear. The masker is intended to remove the contribution of the non-test ear in eliciting a response from the respondent by elevating the threshold of the non-test ear. Behaviourally, multiple stimulus and masking levels are used to ensure that the non-test ear is not contributing

to the response. Masking can also be implemented in tone pip ABR testing; however, clinical testing time is much more limited, and a modified masking approach is needed. Effective clinical masking levels for adults using AC and BC behavioural testing methods are well established. The amount of masking needed to eliminate BC ABR responses in infants at different frequencies is unknown but critical for the development of masking procedures for clinical populations. Measurement of masker levels for BC stimuli for infants will also contribute to our knowledge of infant-adult maturational differences. The overall objective of the present study is to help improve our confidence in determining ear- and frequency-specific information to ensure intervention can be implemented in a timely manner when an infant is identified with hearing loss.

This review will include an overview of four areas that are important to the understanding of the current study. These areas include: bone-conduction hearing mechanisms, skull properties and their effects on interaural attenuation, masking principles, general background information about the ABR and its use in the pediatric population.

1.2 Bone-Conduction Hearing Mechanisms

As shown in Figure 1.1, sound can reach our cochleae via AC or BC pathways. Bone-conducted (BC) vibrations are generally thought to bypass the outer and middle ear portions of our peripheral auditory system, but some BC pathways allow energy to be transmitted through the outer and middle ear portions as well. Due to the ease in which BC energy travels to and activates the basilar membrane, the differences in transmission of sound energy between air and bone is crucial in clinical audiology for an audiologist's ability to differentiate site of lesion of the conductive nature, such as the presence of air-bone gaps.

Figure 1.1 Schematic representation of the mechanisms of bone-conduction hearing. Presented with permission from Stenfelt & Goode (2005), Bone-conducted sound: physiological and clinical aspects, *Otology & Neurotology*, 26(6), p. 1252.

There are different school of thoughts on how BC energy is transmitted to the cochlea (Figure 1.1), and these mechanisms can be classically classified into osseous and non-osseous modes (Vento & Durrant, 2009). The three osseous mechanisms are distortional-compressional (Kirikae, 1959; Tonndorf, 1966, 1968), inertial (translatory) mode (Barany, 1938; Wever & Lawrence & Von Békésy, 1954; Kirikae, 1959; Tonndorf, 1966), and the osseotympanic mechanism. Allen and Fernandez (1960), and Brinkman, Marres, and Tolk (1965) each described separate actions in how BC hearing is attributed to one mode. In the normal ear, all these modes are integrated to produce the BC hearing phenomenon, with various degrees of amplitude and phase modifications. However, if one or more of the components of the skull or

modes are abnormally affected, such as a missing part of the ear or functionality, then BC is affected negatively. When a bone conductor contacts the head and produces a stimulus, the ensuing sound energy causes the skull to vibrate and displace the surrounding air. At this point, the radiated sound energy, specifically frequencies above 2000 Hz, has emanated through the air and into the external ear canal, which causes deformations of the ear canal walls (Lightfoot, 1979; Bell, Goodsell & Thornton, 1980; Shipton, John & Robinson, 1980). Consequently, these changes act on the tympanic membrane as if the sound was originally an air-conducted (AC) sound.

Spectral content of BC sound affects how it is transmitted through the external ear canal. For example, Khanna, Tonndorf, and Queller (1976) used AC sound to cancel BC sound in the external ear canal for low frequencies below 700 Hz, which supports that most of low-frequency BC hearing is due to the external ear canal; thus, explains why occlusion of the external ear canals plays a role in the low frequencies specifically. In adults, sound pressure for frequencies below 1000 Hz are amplified when ears are occluded (Huizing, 1960; Elpern & Naunton, 1963; Tonndorf, 1966; Khanna, Tonndorf & Queller, 1976), which essentially eliminates the unoccluded canal's high-pass filter (Tonndorf, 1966; Gelfand, 1981, p. 66); however, young infants do not demonstrate a significant occlusion effect (Small, Hatton & Stapells, 2007). Specifically, when ASSR thresholds were determined in infants with occluded ears and non-occluded ears, the thresholds did not change significantly, even though sound pressure levels increased significantly when occluded. Infant ear canals are narrower and shorter than the adult ear (Anson & Donaldson, 1981; Keefe, Bulen, Campbell & Burns, 1994), which explains the increase in resonance of the ear canal when compared to adult ear canals (Kruger, 1987; Kruger & Ruben, 1987; Keefe et al., 1994). Also, when infant ears are occluded, the lack of occlusion

effect (i.e., no increase in low frequency amplitude) may be attributed to the infant's compliant ear canal wall, which is suggested to make low-frequency energies easily absorbed into the canal walls (Keefe, Bulen, Arehart & Burns, 1993; Keefe et al., 1994). In the present study, the ears were occluded for both infants and adults for unmasked and masked conditions to control for any occlusion effects.

Huizing (1960) and Tonndorf (1966) each had a different explanation for the occlusion phenomenon. As noted earlier, Tonndorf postulated that both the mass effect of the air in the ear canal and the impedance of the air and tympanic membrane produce a high-pass filter. When an occlusion occurs in the same air space that is in the ear canal, the acoustic properties are modified, leading to the elimination of the high-pass filter, which then leads to an increase of low-frequency sound energy. Huizing (1960) suggested that it is the resonances and antiresonances that determined the acoustic properties above 2000 Hz.

Stenfelt and colleagues revealed a 10-15 dB decrease in sound pressure in the ear canal with BC stimuli when the cartilaginous portion of the external ear canal was removed, which supports the idea that the vibrations of the cartilaginous portion plays a major role in the transfer of sound energies in the canal, especially at low frequencies (Tonndorf, 1966; Stenfelt, Wild, Hato, et al., 2003). Furthermore, Khanna et al. (1976) demonstrated that when a BC tone was used to cancel an AC tone subjectively, the sound in the external ear canal was cancelled for frequencies below 700 Hz, which suggests that lower-frequency BC sound is transmitted through the ear canal. As for high frequencies, the external ear canal is not the main route, as exemplified by Huizing (1960).

1.3 Skull Maturation and Transcranial Attenuation

The infant skull comprises multiple bony plates that are not fully fused until later in life. Each plate grows and eventually fuses with neighbouring plates. Before this occurs, fibrous joints known as sutures affords the bony plates the ability to grow evenly and symmetrically. As the plates develop, they fuse together by ossification, but fontanelles are observable before this fusing is complete, which usually occurs in early adulthood (Steele & Bramblett, 1988; Carlson, 1999). Fontanelles are gaps where multiple unfused bony plates meet and are normally covered by a tough membrane that protects the underlying soft tissue and brain. The presence of sutures explains the rapid development of the infant skull, as it is a means of sliding apart the plates to allow further ossification (Opperman, 2000). There are six fontanelles: (1) the anterior fontanelle or the “soft spot”, (2) the posterior fontanelle, (3-4) two posterolateral fontanelles, and (5-6) two anterolateral fontanelles.

It is thought that the softer connective tissue of the sutures of the infant skull affords the temporal bone to oscillate more in isolation, which better prevents the dissipation of the BC energy to the rest of the other bony plates; this is observed as a more intense signal to the ipsilateral cochlea (Stapells & Ruben, 1989; Stuart, Yang & Stenstrom, 1990; Foxe & Stapells, 1993; Stuart, Yang & Botea, 1996; Small & Stapells, 2008a; 2008b). The fontanelles are also a source of escaped auditory energy, leading to an observable increase in transcranial attenuation when compared to adults (Sohmer Freeman, Geal-Dor, Adelman & Savion, 2000). Note: transcranial attenuation is commonly referred to as interaural attenuation (IA) clinically.

Multiple click or tone pip ABR studies have investigated IA in infants, and they reveal prolonged wave V latencies and reduced amplitude measurements in the contralateral channel when compared to the ipsilateral channel which is partly explained by greater BC IA (clicks:

Yang, Rupert & Moushegian, 1987; Picton, Durieux-Smith & Moran, 1994; Stuart, Yang & Botea, 1996; tone pips: Stapells & Ruben, 1989; Foxe & Stapells, 1993). For BC ASSRs, Small and Stapells (2008b) also revealed significant ipsilateral-contralateral asymmetries for infants. For adult BC ASSRs, contralateral responses, when compared to the ipsilateral channel, revealed no consistent ipsilateral-contralateral pattern (i.e., no ipsilateral-contralateral differences, ipsilateral response greater than the contralateral response, or contralateral response greater than the ipsilateral response). Frequency also appears to affect the BC ASSR ipsilateral-contralateral pattern to some degree in infants; asymmetries were most pronounced at 500 and 4000 Hz (Small & Love, 2014). Other factors that contribute to ipsilateral-contralateral asymmetries will be discussed in the ABR section.

As helpful as wave V asymmetries may be between ipsilateral and contralateral recordings, there are clinical situations where it may not be possible to rely on these differences. Contralateral masking is recommended for the cases where ipsilateral-contralateral asymmetries cannot isolate the test ear from the non-test ear.

1.4 Masking

As mentioned earlier, IA describes how much sound energy decreases as it travels across the skull. The adult skull has fused sutures and acts as a conductor; as a result, adults have practically no attenuation for BC signals (Nolan & Lyon, 1981). In contrast, infants have unfused sutures and other immaturities in their skull development; therefore, infants have greater attenuation of BC signals (Yang, Rupert & Moushegian, 1987; Small & Stapells, 2008a). When a bone oscillator is placed on one mastoid, the signal can activate the cochlea on that same side (i.e., the test ear); it can also travel across the skull and activate the cochlea that is contralateral

to the side of the bone oscillator (i.e., the non-test ear). If it is not clear which ear is responding to the stimulus, the response obtained from the assessment can be difficult to interpret. One way to remedy this is to administer clinical masking to isolate the test cochlea.

Masking is a psychoacoustic phenomenon whereby the threshold for detection of the signal is increased due to the presence of another sound (i.e., the masker) (Lidén, Nilsson & Anderson, 1959a). In our everyday environments, what we consider to be the background noise can be described as a masker, where the primary sound that we are interested in hearing is obscured by the background or masker noise. The amount of masking that is present determines the listener's ability to detect or discriminate the primary signal, and this masking ability can be determined by the masker's intensity, frequency spectrum, and bandwidth (Greenwood, 1961). An increase in threshold for a given signal in the presence of masking noise is evidence that the ear is sensitive to the masker (Moore, 1997; Nozza & Henson, 1999). When the intensity of a masker is increased by a certain amount, the same amount will increase masked thresholds for the detection of the signal, except for very low masker levels (Hawkins & Stevens, 1950).

Appropriate bandwidth and spectral composition are also required for the masker. Because the cochlea performs spatial filtering on incoming sounds (von Békésy, 1960), where the high and low frequencies are represented basally and apically, respectively, masking is optimal when the masker occupies the same frequency region as the signal, (i.e., the two stimuli are not distinct at the level of the basilar membrane). A masker's bandwidth that is too wide may not always be optimal. For example, additional frequencies far from the center frequency of the signal do not help in providing additional masking and may reach patient tolerance levels sooner than if a masker with a narrower bandwidth had been used. As such, a narrower masker with equal energy at all frequencies that it comprises may be needed, especially if the masker is

as wide as the critical bandwidth (Fletcher, 1953; Lidén, Nilsson & Anderson, 1959b). For the current study, the signal is a tone pip; a wideband white noise masker was required to encompass all the frequencies present in the signal. Using a narrowband masker in this case would result in undermasking.

For pure-tone audiometry, different masker types are used depending on the signal presented. For example, narrowband noise is used to mask pure-tones and filtered white noise is used for speech stimuli. Effective masking levels (EMLs) are determined by presenting the signal and the masker in the same ear. The lowest level of masker that just masks the signal is the EML. Effective masking refers to the sound pressure level of a noise required to mask a signal to 50% probability of detection (ANSI S3.6, 1996). Most clinical audiometers are calibrated to these values. The typical clinical scenario is that masking is applied in the non-test ear to determine accurate thresholds for the test ear. The minimum masking level is the amount of masking that just prevents crossover of the test signal to the non-test ear. To determine the EML, the masker is increased in 5-10 dB steps until the test-ear threshold no longer shifts. When the masking level is high enough to crossover to the test ear and elevate its threshold, this is referred to as overmasking. The range of masker levels in between under- and overmasking is referred as the plateau (Hood, 1960). In the present study, when we use the term EML, we are referring to the lowest binaural AC masking level needed to isolate the test cochlea when conducting BC ABRs. The rationale for using a binaural masker will be explained in detail in the ABR section.

So far, the maskers described here are energetic maskers, which interact with the signal at the level of the cochlea. There are other forms of masking, such as informational masking, which occurs more centrally; however, only energetic masking was investigated in the present

study. Due to basilar membrane non-linear properties, such as the actions of the outer hair cells responding to stimuli, increasing the masker level also produces a phenomenon known as upward spread of masking where more and more of the higher frequencies are masked (e.g., Galambos, 1956; Dallos, Evans & Hallworth, 1991; Dallos, 1992; Dallos & Evans, 1995; Dallos et al., 1997). The travelling wave grows larger in amplitude as it travels from the base of the cochlea to the apex, towards its peak. Once the peak is reached, the amplitude drops off rapidly as the travelling wave travels apically. Wegel and Lane (1924) confirmed that low-frequency tones more readily masked high-frequency tones, and not the other way around, due to the shallower amplitude growth leading up to the peak.

Partial masking is when masking does not change the threshold of the signal detection, but a reduction in the signal intensity is observed (Scharf, 1971). The present study was designed to have the signal presented at a constant level, and the masker delivered at varying levels until the level at which the masker eliminated the presence of an ABR response was found. Partial masking in this case would be any masking scenario where the ABR response was diminished, but not yet eliminated (i.e., reduced amplitudes and increased latencies of wave V) (Gould & Sobhy, 1992).

Other masking parameters to consider include temporal effects. For example, simultaneous masking is when the masker and signal are presented at the same time. There is also non-simultaneous masking, and these are backward masking, forward masking, or a combination of the two. Backward masking occurs when the signal precedes the masker, whereas forward masking occurs when the masker precedes the signal. Masking is more effective when both backward and forward masking are combined, than when the two masking paradigms are summed separately (Pollack, 1964; Elliott, 1969; Wilson & Carhart, 1971;

Robinson & Pollack, 1973; Pastore, Harris & Goldstein, 1980; Penner, 1980; Cokely & Humes, 1993; Oxenham & Moore, 1994, 1995). Due to clinical applicability, simultaneous masking will be used in the current study.

Only two electrophysiological studies on normal-hearing infants, both using ASSRs and binaural masking, have been conducted to estimate EMLs. Hansen and Small (2012), and Small, Smyth, and Leon (2014) reported EMLs for 1000 and 4000 Hz, and 500 and 2000 Hz, respectively, as summarized in Table 1.1. From the table, it is evident that a higher masking level is required in infants than adults given the same stimulus level at lower frequencies; as frequency increases, the amount of masking required for infants compared to adults becomes less. Currently, there are no published ABR studies directly looking into estimating EMLs in the normal-hearing infant population; others, such as Lightfoot, Cairns, and Stevens (2010) determined indirectly the amount of masking required and have created a calculation for clinicians to use to determine the adequate amount of masking. The current study attempts to directly estimate EMLs for 500 and 2000 Hz, which in the BCEHP protocol are given the highest priority for BC infant ABR assessment.

	Frequency (Hz)			
	500	1000	2000	4000
Infant	81	68	59	45
Adult	66	63	59	55

Table 1.1 Recommended effective masking levels in dB SPL from the two studies on auditory steady-state response masking; bone-conduction stimulus presented at 35 dB HL for 500, 1000, 2000, and 4000 Hz carrier frequencies for infants and adults. The masker was presented binaurally.

Yang, Rupert, and Moushegian (1987) illustrated the maturational differences between infants and adults by observing the effect of masking on BC click-ABR latencies. Their study revealed that (1) an increase of masker level from 40 to 50 dB nHL resulted in a significant increase of wave V latencies in newborns, but only a small increase in adults, and (2) when signal-to-noise ratio was fixed at -15 dB, a decrease of both signal and masker levels by 10 dB produced a significant increase in wave V latencies in adults, but almost no change was observed in newborns. These observations are consistent with the unfused sutures present in the immature infant skull and the fully developed, and sutured skull of adults. These differences suggest that the stimulus presented at 35 dB nHL at the temporal bone activated both cochleae effectively in adults, whereas only negligible energies reached the contralateral cochlea in infants. Yang and colleague's (1987) clinical recommendation is to assume the adult IA to be 0 dB, and that masking of the non-test ear is to be considered. For one-year old infants, masking is suggested, except for low intensities, and for neonates, masking is likely not needed for intensities lower than 25 dB nHL; however, this will depend on BC IA for the individual (Yang, Rupert & Moushegian, 1987). It is important to note that Yang, Rupert, and Moushegian (1987) used broadband stimuli to elicit the ABR; however, recent frequency- and amplitude-modulated ASSR research data shows that masking effects depend on frequency and age. For example, masking is more effective for infants than adults at 4000 Hz (Hansen & Small, 2012; Small, Smyth & Leon, 2014). Because the click stimulates all frequency regions of the basilar membrane, a clinician may be undermasking some regions of the basilar membrane and overmasking others, making the results difficult to interpret.

1.5 Auditory Brainstem Response

As mentioned earlier, one of the recommended physiological measures is the ABR, which is the response to activation or electrical changes of the auditory pathway up to the level of the brainstem. Because it takes time for the auditory pathway to transmit stimulus details from the level of the cochlea to the brain, latency is a key measurement that helps determine the integrity of the auditory pathway. Previous clinical studies investigating near-field and far-field potentials demonstrated lengthened latencies occurred when a lesion was present at specific sites along the auditory pathway.

An ABR waveform have several distinct peaks. Studies provide support that peak III is the earliest manifestation of neural activation at the level of the brainstem, specifically the cochlear nucleus and the superior olivary complex, thus, longer latency responses originate from sources further along the auditory system (Garg, Markand & Bustion, 1982; Møller & Jannetta, 1983a; 1983b; Møller & Burgess, 1986; Møller, Jannetta & Sekhar, 1988). Peak IV originates from the direct connection from the cochlear nuclei to the inferior colliculi in addition to third-order neurons within the superior olivary complex, while peak V reflects the contribution of multiple sources, including the lateral lemnisci via the superior olivary complexes and its ascended connection in the midbrain to the inferior colliculi (Møller, Jho, Yokota & Jannetta, 1995; Melcher & Kiang, 1996).

As discussed earlier, the harmful effects of untreated or unidentified hearing loss on children and their families is well-established (Yoshinaga-Itano, Sedey, Coulter & Mehl, 1998; Yoshinaga-Itano & Gravel, 2001; Kennedy, McCann, Campbell, Kimm & Thornton, 2005). Numerous studies provided evidence of successful estimation of pure-tone audiograms from tone pip ABR threshold with reasonable accuracy (e.g., Stapells & Oates, 1997, Stapells, 2000; 2011;

Hatton, Janssen & Stapells; 2012). Although considered the best practice technique for diagnosing type and degree of hearing loss in infants who do not pass their hearing screening (Canadian Working Group on Childhood Hearing, 2005; Joint Committee on Infant Hearing, 2007), diagnostic ABRs can be compromised by the presence of ANSD and other neurologic involvement. In these cases, the ABRs do not truly reflect cochlear or behavioural sensitivity (Rance, 2005; BCEHP, 2012; OIHP, 2016).

Since its first publications in the 1970s, tone pip AC ABR testing has been used clinically, but not without concerns regarding the accuracy of the thresholds obtained from frequency-specific ABRs (Stapells, 2011; Baldwin & Watkin, 2013). Many audiologists use only the click stimulus as opposed to more frequency-specific options because of its ability to elicit a large ABR response sometimes when the child awake (Elsayed et al., 2015). However, the click stimulus is broadband, which tends to activate most of the cochlea at once, rather than a specific region of the basilar membrane; this makes it difficult to determine which frequency the broadband click-ABR threshold truly represents (Stapells, 2011). There is evidence that tonal or other frequency-specific stimuli is preferred to the click for threshold searches (Picton, 1978; Eggermont, 1982; Picton & Stapells, 1985; Stapells, 1989; Stapells & Oates, 1997; Stapells, 2000). The BC tone pip ABR has a history of regular clinical use since at least the 1980s (Gravel, Kurtzberg, Stapells, Vaughan & Wallace, 1989; Stapells, 1989; Stapells & Ruben, 1989).

Clinical ABR guidelines and procedures are well-established (e.g., Canada: BCEHP, OIHP; USA: ASHA) and can be used to determine the degree, type, and configuration of hearing loss. According to a 2014 Canadian Infant Hearing Task Force a report, two provinces —British Columbia and Ontario — each have implemented an excellent early hearing program, especially

when it comes to setting standards and guidelines. From the BCEHP ABR protocol (BCEHP, 2012), an AC 2000-Hz stimulus presented at the minimum response level for infants (30 dB nHL) is required as the first step in the protocol. Regardless of whether the response is present or absent, the opposite ear is also assessed at this minimum response level. If the response is present in both ears, hearing within normal limits at 2000 Hz is confirmed. If there is no response in either ear, the next prioritized step is to present a BC stimulus at 2000 Hz at the minimum response level (30 dB nHL) in the ear with no AC response to 2000 Hz. If still no BC response is present at the minimum level, then the audiologist would proceed to present the BC stimulus at the maximum level available. If no response is present at the maximum BC level, BC testing is complete for this frequency and indicates primarily sensorineural hearing loss, and BC testing at 2000 Hz for the ear is complete. Otherwise, a threshold search is required for BC at 2000 Hz for this ear. This threshold search can be done either at this point of the procedure, or after the conclusion of the AC 2000-Hz threshold search. The tester would return to conducting AC testing at 2000 Hz for the ear with an absent response at the minimum level to establish the threshold. Once the threshold is determined, then AC 2000 Hz is complete. 500 Hz BC thresholds searches are also mandatory if 500 Hz AC thresholds are elevated; testing at this frequency follows the protocol outlined for 2000 Hz. Regarding BC ABR, testing 1000 and 4000 Hz are notably absent from both the BCEHP and Ontario Infant Hearing Program (OIHP) protocols. This is due to the limited data available for infants at these two frequencies. Ferm, Lightfoot and Stevens (2014), and Cone-Wesson & Ramirez (1997) have provided preliminary data (14-20 infants); see Table 1.2 summary for other studies showing the mean BC tone-pip ABR thresholds in infants with normal BC hearing. Foxe and Stapells (1993) revealed that ABR thresholds were significantly lower (i.e., better) for BC 500-Hz tone pips, when compared to

thresholds for 2000-Hz BC tone pips. Also, wave V latencies for the 500-Hz tones were shorter when compared to adults (latencies were similar for responses to 2000-Hz tones in both infants and adults), which suggested an increased effective intensity for infants at 500 Hz. Comparing 500 and 2000 Hz, it is evident that as frequency increases, the mean threshold in infants increases as well, which suggests that infant hearing is more sensitive at lower frequencies. Even with just 500 and 2000-Hz BC thresholds, the protocol outlined in the BCEHP and the OIHP is adequate for determining the nature of hearing loss and for distinguishing among sensorineural, conductive, and mixed hearing losses (Gravel, 2002; JCIH, 2007; Hatton, Janssen & Stapells, 2012).

BC TONE-ABR STUDY	500	1000	2000	4000
<i>Weighted means across all studies</i>	3 (140)	5 (14)	14 (94)	7 (20)
Stapells & Ruben, 1989 (normal group)	2 ^a (24)		6 ^a (24)	
Stapells & Ruben, 1989 (all infants)	-2 ^a (66)		4 ^a (66)	
Foxe & Stapells, 1993	3 ± 10 (9)		14 ± 7 (8)	
Cone-Wesson & Ramirez, 1997 (age: 1–2 days) <i>Standard deviations estimated from graph in original study</i>	-15 ± 10 ^b (24)			7 ± 7 ^b (20)
Vander Werff et al., 2009	11 ± 8 (40)		17 ± 7 (40)	
Ferm et al., 2014 (age <2 months) ^b	3 ± 7 (19)	5 ± 8 (14)		
Valeriotte & Small, 2015 (normal group, age 0–6 months)	10 ± 8 (24)		15 ± 10 (22)	

Table 1.2 Bone-conduction auditory brainstem response mean thresholds (dB nHL) ± standard deviation (where available) elicited to tone pips in infants with normal bone-conduction hearing. Number of participants in brackets. Weighted means exclude Stapells and Ruben (1989) non-normal results. Table from *Comprehensive Handbook of Pediatric Audiology, Second Edition* (p. 515) by Anne Marie Tharpe and Richard Seewald. Copyright © 2017 Plural Publishing, Inc. All rights reserved. Used with Permission.

Estimation of hearing thresholds from ABRs is done by interpreting replicability of waveforms for a range of AC and BC stimulus levels; most commonly, this is done visually combined with some objective measuring of signal-to-noise ratio and residual noise. Several repetitions allow for an averaging of these changes, and over time, the changes that are due to the stimulus get enhanced, while the electrical changes at the level of neural source that are due to random events (i.e., not due to the stimulus itself) are averaged out. Waveforms can be obtained

from EEG recordings both ipsilateral and contralateral to the stimulus; 2-channel recordings are helpful for observing the asymmetries in ipsilateral-contralateral responses discussed earlier. Due to the BC ABR montage, the set-up (i.e., 2-channel recording as opposed to 1-channel) often affords clinicians the ability to differentiate which cochlea is responding to the BC stimulus. As mentioned earlier, infant skulls have sutures that are not fused, which attenuates sound energy as it travels from one mastoid to the other (Yang, Rupert & Moushegian, 1987; Small & Stapells, 2008b). Effectively, the sound that ends up at the cochlea contralateral to the side with the bone oscillator is expected to be at a lower intensity. Another contributing factor to this asymmetry is the changes in dipole orientation of the ABR neurogenerators in the brainstem (Edwards, Durieux-Smith & Picton, 1985; Ponton, Moore, Eggermont, Wu & Huang, 1994; Ponton, Moore & Eggermont 1996; Moore et al., 1996). This asymmetry is detectable when comparing the ipsilateral and contralateral waveforms. In normal-hearing infants, there should be a difference between the ipsilateral-contralateral waveforms; the ipsilateral response has its wave V occur earlier and produces a larger amplitude compared to the contralateral response (Edwards, Durieux-Smith & Picton, 1985; Stapells, 1989; Stapells & Mosseri, 1991; Foxe & Stapells, 1993). If the opposite occurs (i.e., larger amplitude and shorter latency is observed in the contralateral waveform), then it can be concluded that the contralateral cochlea is responding to the stimulus, and not the ipsilateral, and thus, a sensory loss is present in the test ear, especially if other physiological assessments show consistent results, such as those from tympanometry and OAEs (Stapells, 1989; Sininger & Hyde, 2009). It is important to consider the presence of the wave V peak itself in the waveform. If an audiologist is testing an infant whose ipsilateral waveform has an absent wave V, but the contralateral waveform has a wave V peak, then this asymmetry is helpful in determining which cochlea is responding to the stimulus.

This asymmetry is accepted as a clinical tool, but this asymmetry disappears as children become older due to skull and neurogenerator maturity.

When children grow old enough for ipsilateral-contralateral asymmetries to disappear or when ipsilateral-contralateral asymmetries are inconclusive in younger infants (e.g., ipsilateral and contralateral responses are similar, contralateral responses are too noisy to interpret), clinical masking is needed to ensure that the non-test ear is not contributing the test ear's hearing assessment. Only two studies have estimated EMLs for BC stimuli and they are both for ASSR (Hansen & Small, 2012; Small, Smyth & Leon, 2014). Direct measurement of EMLs for ABR have not been investigated and it is important to establish EMLs to reduce time and avoid under- or overmasking, especially because infants are unlikely to sleep long enough for the audiologist to determine minimum masking levels and a masking plateau as is done for adult behavioural testing. In the present study, binaural masking was used to establish EMLs to determine the lowest level of masker that would eliminate contributions to the ipsilateral and contralateral recordings of the ABR originating from either ear. For adults, the EML is the lowest level they report no longer hearing the signal (wherever they hear it). Because we used a single stimulus level in infants, rather than determining unmasked thresholds for each ear as you would for adult behavioural testing, we can only be sure both ears are effectively masked if we apply masking to both ears.

There is support for the use of another physiological method — the ASSR may be a viable clinical tool due to its ease in conducting the testing and interpreting the results. Perhaps the ASSR could be relied upon in conjunction with ABR testing; however, further research on clinical populations is required. Currently, BC ASSR thresholds for normal-hearing infants and adults are available (Small & Stapells, 2005; 2006; 2008a). As mentioned previously, BC EMLs

for ASSR in normal hearing infants have also been established (Hansen & Small, 2012; Small, Smyth & Leon, 2014). This is crucial, especially for ASSR assessment, because BC ASSR ipsilateral-contralateral asymmetries are not consistent for 1000 and 2000 Hz but are at 500 and 4000 Hz. More work regarding ipsilateral-contralateral asymmetries using BC ASSR is needed for infants with hearing loss before the ASSR can be used clinically (Small & Love, 2014).

1.6 Rationale for Thesis

The purpose of this thesis is to determine EMLs for BC stimuli for normal-hearing infants, under 18 months of age, and adults, using the ABR technique. There are studies that investigated EMLs for BC stimuli using the ASSR, but not for the ABR. Although clinicians can often depend on ipsilateral-contralateral asymmetries to determine which cochlea is responding in an ABR assessment, masking can better isolate the test cochlea and improve the accuracy of ABR assessments when ipsilateral-contralateral findings are not clear. Obtained through the presentation of binaural simultaneous AC white noise, this study's EMLs will provide further information on how much masking is appropriate to use clinically when obtaining ear and frequency-specific BC ABR thresholds. A comparison of EMLs between infants and adults can further substantiate previous findings regarding maturational differences.

Chapter 2: Effective Masking Levels for Bone-Conduction Auditory

Brainstem Response Stimuli in Infants and Adults with Normal Hearing

2.1 Materials and Method

2.1.1 Participants

Twenty-seven adult (mean age: 24 years; age range: 18-54 years) and twenty-six infant (mean age: 23 weeks; age range: 5-47 weeks) with normal hearing in both ears participated in the present study. The loose coupling of the bone oscillator to the participant's temporal bone region lead to the exclusion of one adult's results at 2000 Hz (20 dB nHL and 30 dB nHL), and another adult's results at 500 Hz (20 dB nHL).

Infants underwent a transient evoked otoacoustic emissions hearing screening using the Otometric Madsen AccuScreen; infants who passed the screening were determined to be low-risk for hearing loss. Two infant participants did not pass the hearing screening due to noise, but each of the infant's parent reported the baby having passed the newborn hearing screening at birth. These infants' results were included, as the results did not differ from those of other infants. Adults who had AC and BC behavioural hearing thresholds ≤ 25 dB HL for 250, 500, 1000, 2000, 4000, and 8000 Hz, and air-bone gaps ≤ 10 dB were included in this study.

2.1.2 Bone-Conduction Stimuli

The RadioEar B-71 bone oscillator was used to present BC tone-pip stimuli to participants. The envelope for the rise, plateau, and fall phases of these stimuli was a 5-cycle Exact Blackman with no plateau and total stimulus duration of 10 000 and 2 500 μ s for 500 and

2000 Hz, respectively. The BC stimuli were generated by the 2-channel SmartEP USB Box set from Intelligent Hearing Systems. Stimuli were presented using an alternating stimulus polarity. The stimulus presentation rate for infants was 39.10/s for both 500 and 2000 Hz, and 9.10/s and 59.10/s for 500 and 2000 Hz, respectively, for adults.

The BC stimulus levels for both infants and adults at 500 Hz were 20 and 30 dB nHL; for 2000 Hz, the levels were 30 and 40 dB nHL for infants, and 20 and 30 dB nHL for adults. Two stimulus levels were presented for each frequency to confirm that the relationship between EMLs and stimulus level was linear. Data from the higher stimulus level at each frequency (30 dB nHL for 500 Hz and 40 dB nHL for 2000 Hz) for the infant group was no longer collected halfway through the data collection process due to the excessive length of time required to complete the recording session. The infant and adult groups shared a stimulus level for each frequency, which was intended to allow comparisons between the two groups. The lowest stimulus levels for each frequency for the infant group were selected based on ‘normal’ maximum levels for ABR, which are the lowest level at which greater than 90% of the population group have responses present (reviewed in Small & Stapells, 2017, p. 541).

The bone oscillator was placed on the posterior region of the temporal bone of the participant. Although Small, Hatton, and Stapells (2007) determined that bone oscillator placement among the superior, supero-posterior, and posterior regions of the temporal bone did not produce significant differences in ASSR thresholds, one region was selected for consistency. A trained lab assistant held the bone oscillator in place for infants, as close to the posterior region as possible, while adults wore an elastic headband to couple the bone oscillator to their head. Small, Hatton, and Stapells (2007) determined that there are no significant differences between the two coupling methods used for infants (handheld) and adults (headband). The amount of

force required to couple the bone oscillator to the skull was 400-450 g (Small, Hatton & Stapells, 2007).

2.1.3 Maskers

AC white noise was presented binaurally using ER-3A insert earphones (50 Ohm) and generated using the Grason-Stadler GSI 16 clinical audiometer. White noise was used because it was clinically available in the Intelligent Hearing System which is used clinically by the BCEHP. White noise from an audiometer was substituted because the ABR system did not allow binaural presentation of masking noise. The insert earphones remained in the ears during the unmasked conditions, as the occlusion effect is negligible in young infants at 500 and 2000 Hz (Small, Hatton & Stapells, 2007; Small & Hu, 2011). The minimum and maximum amount of masking used in this study were 22 and 82 dB SPL, respectively.

2.1.4 Calibration

The BC stimuli (in dB re: 1 μ N) were calibrated using BCEHP targets and a Brüel & Kjær 4930 artificial mastoid and a Larson-Davis 824 sound level meter. The targets for 500 and 2000 Hz are 67 and 49 dB ppe, respectively. The bone oscillator was coupled to the artificial mastoid with 550 g of force.

The insert earphones used to deliver white noise were calibrated in dB SPL using the Larson-Davis 824 sound level meter and a GRAS Sound & Vibration RA0113 1-inch 2-cc coupler. The insert earphones and B71 BC transducer used to deliver pure-tones for the screening of normal hearing in adult participants were calibrated in RETSPLs, and dB re: 1 μ N corresponding to 0 dB HL (ANSI S3.6-1996), respectively. In the present study, real-ear-to-

coupler differences were not obtained for each participant for the purpose of converting masker dB SPL measured in the coupler to dB SPL in the individual ear canal as these comparisons were already made in a previous BC ASSR studies at 500, 1000, 2000 and 4000 Hz (Hansen & Small, 2012; Small, Smyth & Leon, 2014). The masker levels obtained in this study can be converted to dB SPL in the ear canal using published real-ear-to-coupler differences.

2.1.5 Recording

ABRs were recorded using the Intelligent Hearing Systems SmartEP hardware (USB Box and Opti-Amp 8002 amplifier) and software (SmartEP). The EEG recording filter settings were set to a high pass of 30 Hz and a low pass of 1500 Hz with a minimum gain of 100 000 X. Artifact rejection was set to exclude sweeps that contained EEG noise that exceeded +/- 15-25 μ V (starting default 25 μ V) for infants and 10-15 μ V (starting default: 15 μ V) for adults within the region of 14.4 – 25.6 ms for 500 Hz, and 3.1 – 25.6 ms for 2000 Hz. The starting default levels were selected to maintain consistency among ABR recordings, and to coincide with BCEHP's protocols regarding infant ABR artifact rejection levels.

A four-electrode montage was used to record the EEG and included inverting electrodes placed on the right (M2 – Channel A) and left (M1 – Channel B) low mastoids, a non-inverting electrode on the high-forehead FCz, and a ground electrode placed at the lateral forehead (greater than 3 cm from the non-inverting electrode). The impedance for each electrode did not exceed 3 kOhm, and the difference in impedance between each electrode did not exceed 1 kOhm. Two-channel ABR recordings (ipsilateral and contralateral to the oscillator placement) were conducted for infants, whereas 1-channel ABR recordings (ipsilateral to the oscillator placement) were performed for adults.

The residual noise and signal-to-noise ratio windows selected differed depending on the frequency and the level of the stimulus. For 500-Hz tone pip stimuli, the windows were set to 10.5 – 20.5 and 14 – 24 ms, at 20 and 30 dB nHL, respectively. For stimuli presented at 30 dB nHL, only the residual noise value provided is valid. These differences in the residual noise windows compensate for stimulus artifact often present at higher BC stimulus levels. For the 2000-Hz tone pip stimuli, the residual noise and signal-to-noise ratio windows were set to 6.5 – 16.5 ms.

Each replication of an ABR recording required a minimum and maximum of 800 and 2000 sweeps, respectively. A minimum of two replications was required per experimental condition. The criterion for a “response-present” was a clear, replicable wave V; for a “response-absent”, the criterion was that no discernible wave V was present (i.e., the waveform should be visually flat), and either each replication had a residual noise $\leq 0.11 \mu\text{V}$, or the averaged (“added”) waveform had a residual noise $\leq 0.08 \mu\text{V}$. Waveforms that did not meet the criteria for either response-present or response-absent were deemed “could not evaluate”. That is, these waveforms did not present a clear wave V, or that they did not have a residual noise that was low enough to be considered a response-absent.

2.1.6 Procedure

Participation in this study involved one to two recording sessions (1-3 hours per session) conducted in the Pediatric Audiology Laboratory at the University of British Columbia. Adult participants and the parent/legal guardian of infant participants read and signed a consent form prior to participating in the study. All the procedures in this study were approved by the UBC Clinical Research Ethics Board.

The ABR recording was completed in a sound-treated booth, where the ambient noise sound levels were 12, 10, 10, and 12 dB SPL for the frequencies 500, 1000, 2000, and 4000 Hz, respectively. Infants and adults slept unsedated throughout the recording phase of the study. Adults slept on a reclining chair, while infants were either held by their parent/legal guardian (stood or seated in a reclining chair) or were placed into a bassinet or stroller provided by the parent/legal guardian. Unmasked and masked ABRs (white noise presented binaurally) were obtained for 500 and 2000 Hz. The presentation order for the stimulus and initial masking levels were randomized for all participants. The initial masking level was randomly chosen from 42, 52, 62, or 72 dB SPL. The masker level was adjusted in 10-dB steps until a response was changed from either a response-present to response-absent, or a response-absent to response-present. The lowest masker level that just produced a response-absent when there was previously a response-present for a masker that was 10 dB lower in level was considered the EML. When an unmasked ABR recording resulted in an averaged waveform with response-absent or “could not evaluate”, masked conditions were not conducted for that frequency and stimulus level.

Sixteen of 27 adults attempted all conditions, where seven of them did not complete at least one condition due to fatigue of wearing the bone oscillator with the headband. One adult was not able to fall asleep for the study. Twenty-two of 27 adults contributed to adult data (e.g., amplitude and latency), including cases where an EML was not obtained.

Twenty-four of 26 infants tested contributed at least partial data for at least one condition; however, only 20 of these infants contributed an EML in at least one condition. Four infants woke up before an EML could be determined and two infants did not fall asleep and did not contribute to any data. Table 2.1 below summarizes the number of infants that contributed data

for each condition and masker level attempted. The EML for 2000 Hz presented at 20 dB nHL for one infant was estimated by subtracting 10 dB from their EML at 30 dB nHL, as this infant woke up before they could be tested at 20 dB nHL (EML linearity was assumed). Two infants had their EMLs determined by adding 10 dB to the masker level because wave V was present but very small and further testing was not possible because the infants woke up. When there was a wave V present at the maximum allowable masker level (i.e., 82 dB SPL), the EML was assigned a value of 92 dB SPL, independent of the size of the wave V amplitude present at 82 dB SPL.

		Masker Level (dB nHL)					
		Unmasked	42	52	62	72	82
500	20 dB nHL*	18	3	16	17	17	11
Hz	30 dB nHL	6	0	3	3	6	4
2000	30 dB nHL*	20	7	18	18	9	2
Hz	40 dB nHL	8	4	7	6	4	2

Table 2.1 Summary of the number of infants that contributed data for each stimulus and masker condition. The infant normal maximum level for each frequency is denoted by “*”.

2.1.7 Data Analysis

Effective masking levels, and ABR amplitudes and latencies were averaged across participants for each frequency and stimulus level, and each age group. Results were only reported if at least 5 participants contributed to the mean. EMLs were compared between age groups and frequencies for BC stimuli presented at 20 dB nHL (500 Hz) and 30 dB nHL (2000 Hz). Unmasked BC infant ABR amplitudes and latencies were compared between frequency for

BC stimuli presented at 20 dB nHL at 500 Hz and at 30 dB nHL at 2000 Hz. Unmasked BC adult ABR amplitudes and latencies were compared between frequency for BC stimuli presented at 20 and 30 dB nHL at 500 Hz, and at 20 and 30 dB nHL at 2000 Hz. Masked BC ABR EMLs were compared between age groups for the following conditions: (1) 500 Hz: stimuli presented at 20 nHL, and (2) 2000 Hz: stimuli presented 30 dB nHL (these conditions were selected to optimize the number of participants contributing to these analyses). Adult and infant residual noise comparisons were made using two-way analyses of variance (ANOVAs). A two-way repeated measures ANOVAs comparing infant amplitudes and latencies between masker level and EEG recording channel for 500 (20 dB nHL) and 2000 Hz (30 dB nHL) was performed. Newman-Keuls *post hoc* comparisons were performed for significant main effects and interactions where appropriate. T-tests were performed to compare the mean EMLs between infants and adults. Missing data were dealt with by using case-wise deletion. Results for all analyses were considered statistically significant if $p < 0.05$.

2.2 Results

2.2.1 Adults

2.2.1.1 Effective Masking Levels

Unmasked and masked responses for two individual adults are shown in Figure 2.1. For these adults, 62 dB SPL of masking was needed to eliminate the ABRs elicited to a 500-Hz stimulus presented at 20 dB nHL and a 2000-Hz stimulus presented at 30 dB nHL. As summarized in Table 2.2, mean adult EMLs were greater for stimuli presented at 500 than at 2000 Hz. As indicated in Table 2.3, for 500 Hz at 20 dB nHL, 90% of EMLs obtained were 72 dB SPL or less (see below); whereas, for 2000 Hz at 20 dB nHL, 100% of EMLs obtained were

62 dB SPL or less. A two-way repeated measures ANOVA indicated that significantly more masking was required for 500 vs 2000 Hz (20 dB nHL): $[F(1, 6) = 18.15, p = 0.005]$. However, for stimuli presented at 30 dB nHL, after case-wise deletion ($N = 5$), the difference between the frequencies did not reach significance $[F(1, 4) = 0.78, p = 0.426]$.

Figure 2.1 Typical responses to 500- and 2000-Hz bone-conduction tones recorded from two adults (A27 and A32) with normal hearing. Responses are from the high-forehead to mastoid ipsilateral to bone oscillator placement. Effective masking levels are indicated in the figure by the star symbols.

	500 Hz		2000 Hz	
	20 dB nHL	30 dB nHL	20 dB nHL	30 dB nHL
Mean	65.0	75.6	52.8	65.1
SD	9.49	7.48	6.41	11.38
Median	62	77	52	62
Mode	62	82	52	62
Min	52	62	42	42
Max	82	82	62	92
N	10	7	13	16

Table 2.2 Summary of descriptive statistics for effective masking levels for bone-conduction auditory brainstem responses in adults.

		Masker Level (dB SPL)						Total
		42	52	62	72	82	92	
500 Hz	20 dB nHL	0	2	4	3	1	0	10
	30 dB nHL	0	0	1	2	4	0	7
2000 Hz	20 dB nHL	2	8	3	0	0	0	13
	30 dB nHL	1	0	12	0	2	1	16

Table 2.3 Summary of the number of occurrences where an effective masking level was obtained at a masker level for adult bone-conduction auditory brainstem response.

2.2.1.2 Amplitude

As shown on Figure 2.2, the amplitude of the ABR wave V decreased as the masking level increased for 500 and 2000 Hz at 20 and 30 dB nHL. The main effect of the masker level on wave V amplitude was significant for the following stimuli: 500-Hz at 20 dB nHL [$F(2, 10) = 17.61$, $\varepsilon = 0.78$, $p = 0.002$], and 2000-Hz at 20 dB nHL [$F(2, 18) = 43.35$, $\varepsilon = 0.74$, $p < 0.0001$], and 30 dB nHL [$F(2, 14) = 12.75$, $\varepsilon = 0.68$, $p = 0.004$]. Pair-wise comparisons for stimuli

presented at 2000 Hz at 20 dB nHL indicated significant decreases in amplitude for the unmasked condition versus 42 dB SPL ($p = 0.0002$) and 52 dB SPL ($p = 0.0001$) masking conditions. The decrease in amplitude with increasing masking noise for 42 versus 52 dB nHL approached significance ($p = 0.076$). Pair-wise comparisons for 2000 Hz at 30 dB nHL also showed significantly smaller amplitudes for the unmasked condition compared to each of 42 dB SPL ($p = 0.049$) and 52 dB SPL ($p = 0.0006$) of masking. The difference in the comparison between 42 and 52 dB SPL of masking was significant ($p = 0.012$). Pair-wise comparisons for stimuli presented at 500 Hz at 20 dB nHL showed significantly larger amplitudes when comparing the unmasked condition vs 52 dB SPL of masking ($p = 0.0006$), and 42 vs 52 dB SPL of masking ($p = 0.002$), but not for unmasked vs 42 dB SPL ($p = 0.1184$).

Adults

Figure 2.2 Mean amplitudes (1 SD) for bone-conduction auditory brainstem responses to 500- and 2000-Hz tone-pip stimuli with increasing masking levels. Residual noise levels (μV) are also shown.

2.2.1.3 Latency

As shown on Figure 2.3, increasing masking levels tended to prolong ABR wave V latencies for 500 Hz. Significant increases in latency were observed at 500 Hz at both 20 [$F(2, 12) = 22.255$, $\epsilon = 0.68$, $p = 0.0009$] and 30 [$F(1, 4) = 39.872$, $p = 0.0032$] dB nHL. For 20 dB nHL, pair-wise comparisons included unmasked vs 42 dB SPL ($p = 0.119$), and 42 vs 52 dB SPL ($p = 0.0006$). For 30 dB nHL, pair-wise comparisons included only unmasked vs 52 dB SPL ($p = 0.0006$).

= 0.003). For 2000 Hz, both stimulus levels (20 and 30 dB nHL) yielded no significant differences in latencies when masker level was increased.

Figure 2.3 Mean latencies (1 SD) for bone-conduction auditory brainstem responses to 500- and 2000-Hz tone-pip stimuli with increasing masking levels.

2.2.2 Infants

2.2.2.1 Effective Masking Levels

Unmasked and masked responses for an individual infant are shown in Figures 2.4a, b. For this infant, 82 and 62 dB SPL of masking was needed to eliminate the ABR at 500 and 2000 Hz, respectively, with stimulus levels 20 and 30 dB nHL, respectively. As shown in Table 2.4, mean infant EMLs for stimuli presented at normal maximum levels were 80 and 62 dB SPL for 500 and 2000 Hz, respectively, indicating that significantly more masking was required to mask out ABRs to 500- versus 2000-Hz stimuli [$F(1, 7) = 56.000$, $p = 0.0001$]. As indicated in Table 2.5, for 500 Hz (20 dB nHL), 92% of infants had an EML of 82 dB SPL or less; whereas for 2000 Hz (30 dB nHL), 93% of infants had an EML of 72 dB SPL or less.

Figure 2.4a, b Typical responses recorded ipsilateral and contralateral to the bone oscillator to 500- and 2000-Hz bone-conduction tones for two infants (I26: 8-weeks; I21: 10-months) with normal hearing. Effective masking levels for responses in the ipsilateral channel are indicated in the figure by the star symbols. Note: For 500 and 2000 Hz, 72 and 62 dB SPL of masking, respectively, resulted in response-absent in the contralateral channel.

	500 Hz		2000 Hz	
	20 dB nHL*	30 dB nHL	30 dB nHL*	40 dB nHL
Mean	79.7	87.0	64.0	74.5
SD	5.99	7.07	8.62	5.00
Median	82	87	62	72
Mode	82	--	62	72
Min	72	82	52	72
Max	92	92	82	82
N	13	2	15	4

Table 2.4 Summary of effective masking levels for bone-conduction auditory brainstem response in infants. There were only two infants where an effective masking level was obtained for 500 Hz at 30 dB nHL, thus, no mode value was calculated. The infant normal maximum level for each frequency is denoted by “*”.

Frequency (Hz)	Stimulus level (dB nHL)	Masker Level (dB SPL)						Total
		42	52	62	72	82	92	
500	20	0	0	0	4	8	1	13
	30	0	0	0	0	1	3	4
2000	30	0	3	7	4	1	0	15
	40	0	0	0	3	1	0	4

Table 2.5 Summary of the number of occurrences where an effective masking level was obtained at a masker level for infant bone-conduction auditory brainstem response.

2.2.2.2 Infant-Adult Effective Masking Level Comparisons

The mean amount of masking needed to eliminate an infant ABR elicited to 500 Hz presented at 20 dB nHL was significantly greater compared to adults at the same stimulus frequency and level: $t(21) = 4.55$, $p = 0.0002$. For 2000-Hz (30 dB nHL), the difference between infant and adult mean EMLs did not reach significance: $t(29) = 0.30$, $p = 0.765$.

2.2.2.3 Amplitude

As shown on Figure 2.5, wave V amplitude in the EEG channel ipsilateral to the bone oscillator decreased with increased masker level for 500 and 2000 Hz infants. Results of a one-way repeated measures ANOVA indicated that the main effect of masker level on wave V amplitudes elicited to stimuli at the normal maximum levels (20 dB nHL at 500 Hz; 30 dB nHL at 2000 Hz), was significant for the ipsilateral channel: 500 Hz at 20 dB nHL [$F(4, 24) = 27.09$, $\varepsilon = 0.92$, $p < 0.0001$]; 2000 Hz at 30 dB nHL [$F(3, 12) = 16.149$, $\varepsilon = 1.00$, $p = 0.0002$]. Pair-wise comparisons revealed a significant difference in amplitudes between unmasked and masked conditions with at least 52 dB SPL of masking for both 500 and 2000 Hz. For 500 Hz, each 10-dB increase in masker level resulted in a significant decrease in amplitude, with the exception of 62 vs 72 dB SPL (52 vs 62 dB SPL, $p = 0.035$; 62 vs 72 dB SPL, $p = 0.229$; and 72 vs 82, $p = 0.013$). However, increasing the masker from 62 to 82 dB SPL was significant ($p = 0.002$). For the 2000 Hz, increasing the masker level from 52 to 62 dB SPL revealed no significant amplitude decrease ($p = 0.448$); however, increasing the masker to 72 dB SPL resulted in smaller amplitudes ($p = 0.035$).

Figure 2.5 Mean amplitudes (1 SD) for bone-conduction auditory brainstem responses to 500- and 2000-Hz tone-pip stimuli with increasing masker levels. Both ipsilateral and contralateral recording channels are shown. Residual noise levels (µV) are also shown.

A significant main effect of masker level on amplitudes for the contralateral channel was observed only for the 500-Hz condition: [$F(4, 16) = 6.68, \varepsilon = 0.70, p = 0.008$]. Due to case-wise deletion and high variability for the unmasked responses, the difference in amplitude comparisons (unmasked vs masked) for the contralateral recording did not reach significance. For 500-Hz, pair-wise comparisons revealed significant amplitude changes when increasing the masker level from unmasked to 72 dB SPL ($p = 0.0083$), and from 52 to 62 dB SPL ($p = 0.040$). When masker level was increased from 62 to 72 dB SPL and 72 to 82 dB SPL, amplitudes did not change significantly.

2.2.2.4 Residual Noise

A two-way ANOVA was performed to determine the effects of age group (adults vs infants), masker level, and the interactions between the two, on residual noise levels. There was no significant difference between the two age groups ($[F(1, 69) = 0.5199, p = 0.4933]$). There was also no interaction effect between masker level and age on residual noise levels: $[F(2, 69) = 1.2041, p = 0.3062]$.

2.2.2.5 Latency

As shown in Figure 2.6 for 500 Hz, latencies increased significantly when masking was introduced at 52 and 62 dB SPL. A one-way repeated measures ANOVA revealed significant main effects for masker level for the ipsilateral ($[F(2, 28) = 43.88, \varepsilon = 0.99, p < 0.0001]$) and contralateral channels ($[F(2, 22) = 49.32, \varepsilon = 0.77, p < 0.0001]$). Pair-wise comparisons of ipsilateral unmasked vs 52 dB SPL ($p = 0.0002$) and 52 vs 62 dB SPL ($p = 0.0003$); and contralateral unmasked vs 52 dB SPL ($p = 0.0001$), 52 vs 62 dB SPL ($p = 0.006$) were significant. For 2000-Hz, both EEG channels ipsilateral ($[F(2, 8) = 2.17, \varepsilon = 1.00, p = 0.177]$) and contralateral ($[F(2, 6) = 6.12, \varepsilon = 1.00, p = 0.036]$) to the bone oscillator revealed no significant changes in wave V latencies as masker level changed.

Figure 2.6 Mean latencies (1 SD) for bone-conduction auditory brainstem responses to 500- and 2000-Hz tone-pip stimuli with increasing levels. Both ipsilateral and contralateral recording channels are shown.

2.2.2.6 Recording Channel

Two-way repeated measures ANOVAs comparing amplitudes and latencies between masker level and EEG recording channel for 500 Hz at 20 dB nHL and 2000 Hz at 30 dB nHL (Table 2.6) revealed that there are significant decreases in amplitudes and prolonged latencies when comparing ipsilateral vs contralateral channels. In contrast, for 2000 Hz, significant differences were only found for latency measures. There were no significant masker level x recording channel interactions.

		Source	<i>df</i>	F	p
500 Hz (20 dB nHL)	Amplitude	Recording Channel	1, 58	12.11	0.001*
		Masker Level	4, 58	24.81	<0.0001*
		Recording Channel x Masker Level	4, 58	1.88	0.127
	Latency	Recording Channel	1, 43	31.29	<0.0001*
		Masker Level	2, 43	27.61	<0.0001*
		Recording Channel x Masker Level	2, 43	0.32	0.727
2000 Hz (30 dB nHL)	Amplitude	Recording Channel	1, 46	2.25	0.1408
		Masker Level	3, 46	26.87	<0.0001*
		Recording Channel x Masker Level	3, 46	1.05	0.378
	Latency	Recording Channel	1, 42	16.11	0.0002*
		Masker Level	2, 42	10.74	0.0002*
		Recording Channel x Masker Level	2, 42	2.85	0.067

Table 2.6 Auditory brainstem response amplitudes and latencies: Two-way ANOVAs showing comparisons between masker level (unmasked, 52, and 62 dB SPL) and amplitudes and latencies obtained from each channel (ipsilateral and contralateral). *Significant ($p < 0.05$).

Chapter 3: Discussion and Conclusion

3.1 Effective Masking Levels

The current study is the first to directly measure EMLs for BC ABR stimuli in infants and adults with normal hearing. For 92% of infant participants, 82 dB SPL of masking presented binaurally completely masked the 500-Hz stimulus when presented at 20 dB nHL. In contrast, 90% of adult participants required only 72 dB SPL of masking noise. Although infant and adult 2000-Hz mean EMLs were not significantly different, when the stimulus level was 30 dB nHL, 93% of infants required 72 dB SPL of masking, whereas 100% of adults only needed 62 dB SPL. These EMLs can be defined as ‘maximum’ EMLs, where an EML provides adequate amount of masking for 90% of the population group or greater. This suggests that most infants require at least 10 dB more masking than adults to completely mask out a 500- or 2000-Hz BC stimulus at any stimulus level.

Mean EML findings also suggest that there are significant age-related differences for 500 Hz, whereas at 2000 Hz, EML differences are negligible. For 500 Hz, mean EMLs are 15 dB greater in infants than in adults. At normal maximum levels, infants require 16 dB more masking at 500 Hz than they require at 2000 Hz. Adults require 11 dB more masking noise for 500 vs 2000 Hz at 20 dB nHL. The results are consistent with the EMLs that Small, Smyth, and Leon (2013) recommend based on their findings on BC ASSR at 500 and 2000 Hz, as they found that considerably more masking is required to mask out a 500-Hz response when compared to 2000 Hz. Some of the extra masking needed for infants may be explained by the greater effectiveness of the BC stimulus on the immature skull in the low frequencies due to the smaller infant temporal bone and the presence of skull sutures (Anson & Donaldson, 1981; Stuart, Yang

& Stenstrom, 1990; Foxe & Stapells, 1993). It has also been established that there are infant-adult middle-ear differences. Infants under six months of age have higher middle-ear impedance and lower middle-ear power transfer than adults, and thus, in comparison to adults, may require an increase in AC masker level to mask out a BC stimulus (Keefe, Bulen, Arehart & Burns, 1993). In contrast to ABR and ASSR findings, behavioural studies support the notion that infants need less masking at lower frequencies than adults (Nozza & Wilson, 1984; Schneider, Trehub, Morrongiello & Thorpe, 1989; Schneider & Trehub, 1992; Allen & Wightman, 1994; Nozza & Henson, 1999). Even accounting for immaturities in the processing of masker noise and the greater effectiveness of 500 Hz at the skull, immaturities in BC EMLs are not yet fully understood. It should be noted that although Small, Smyth, and Leon (2014) used narrowband maskers for their ASSR study rather than white noise, it is unlikely that the differences in masker type explained any of the observed infant-adult differences in the present study as infant critical bands at 800 and 4000 Hz do not differ from adult ones significantly (Schneider, Morrongiello & Trehub, 1990). Overall, the mechanisms influencing the need for greater masking at 500 versus 2000 Hz in infants in the present study are likely similar to the mechanisms influencing the ASSR EML findings from Small, Smyth, and Leon (2014).

Prior to the present study's direct measurement of infant EMLs, attempts were made to calculate the amount of masking needed in infant ABR assessments. The National Health Service of the United Kingdom implemented guidelines for ABR assessment as part of their newborn hearing screening program (National Health Service, 2013). One of the guideline's contributors, Lightfoot, also produced an Excel-based calculator for clinicians to use in determining the appropriate amount of masking needed; the calculator can be found on the British Academy of Audiology website (Lightfoot, 2019). The calculator was based on

Lightfoot's findings of noise levels required to mask AC stimuli in normal-hearing adults (Lightfoot, Cairns, Stevens, 2010). Lightfoot implemented several correction factors into his calculator to determine the amount of masking needed when assessing an infant, such as a correction factor for age-related IA, which can be 20 to 30 dB higher in babies (Yang, Rupert & Moushegian, 1987; Webb, 1993; Small & Stapells, 2008a); smaller ear canals, which raises the masker level due to lower ear canal volume (Sininger, Abdala & Cone-Wesson, 1997); BC age correction (Webb, 1993; Ferm, Lightfoot & Stevens, 2013); and air-bone gaps.

When the Excel calculator and the maximum EMLs recommended from the current study are compared for 2000 and 500 Hz, the calculator predicts at least 7 and 12 dB less masking is needed compared to the direct measures of EML found in the present study. Although Lightfoot incorporated correction factors, the discrepancy between the predicted and actual EMLs are likely due to Lightfoot et al. (2010) collecting masking levels behaviourally from adults. It has been shown that behavioural responses differ from electrophysiological and psychoacoustical responses in terms of detection levels and masking effects (ABR: Gorga, Kaminski, Beauchaine & Jesteadt, 1988; Pinto & Matas, 2007; ASSR: Hansen & Small, 2012; Small & Hansen, 2012). For example, Gorga et al. (1988) found that ABR thresholds were higher than behavioural thresholds for all frequencies, especially for lower frequencies. Small and Hansen (2012) also found that much less narrow-band masking was needed to eliminate BC ASSR stimuli behaviourally compared to electrophysiologically. Therefore, it can be difficult to accurately predict infant ABR masking levels using adult behavioural thresholds as a starting point.

The present study found that only one BC level, 20 dB nHL at 500-Hz, could be safely masked out using a binaural masker, as higher stimulus levels would require masker levels to exceed 82 dB SPL. Likewise, only BC levels up to 40 dB nHL at 2000 Hz could be effectively

and safely masked out. It should also be noted that attempting to mask tone pip stimuli using white noise has limitations, as the ratio of masking effect to overall sound-pressure level (i.e., masking efficiency) is low relative to narrowband noise (Lidén, Nilsson & Anderson, 1959b). This means that broadband white noise requires significantly higher and physiologically undesirable overall sound-pressure level than narrowband noise to mask. Conventional behavioural audiometry uses pure-tone stimuli and narrowband noise as a masker when masking is required, thus, overall, it is easier to mask in behavioural audiometry before reaching uncomfortable levels than when conducting ABR or ASSR assessments. However, it may be possible to mask out responses for 500 Hz at 30 dB nHL and 2000 Hz at 50 dB nHL in a clinical scenario where masking is only applied to the non-test ear. It may be possible to use 10 dB less masking because we can probably safely speculate that the test signal will attenuate by at least 10 dB before stimulating the non-test ear.

Although the ABR assesses the auditory pathway up to and including the auditory brainstem, it does not evaluate the status of the pathway leading up to the cortex from the brainstem. This suggests that higher cortical processes may be at play, such as fatigue, attention, and working memory (Berti & Schröger, 2003; Wright & Fitzgerald, 2004); these factors may affect behaviourally-obtained masking levels such that the signal needs to be greater to detect it in the presence of noise compared to the ABR (Small & Hansen, 2012). In contrast, attention to auditory stimulus does not change either the amplitude or latency characteristics of wave V of the ABR (Picton, Hillyard, Galambos & Schiff, 1971; Picton & Hillyard, 1974; Hillyard, 1981; Kuk & Abbas, 1989). Although the calculator attempts to account for multiple maturational factors, the present study obtained EMLs for BC ABRs directly, which helps minimize the

introduction of error compared to determining EMLs indirectly using multiple correction factors added to adult behavioural threshold data.

The linearity of EML with stimulus level has been established in previous studies (Hansen & Small, 2012; Small, Smyth & Leon, 2014), and was observed in the present study. Consequently, predicting EML for stimulus not tested in the present study can be easily calculated (although, there is little room for increasing masker levels before exceeding safe limits). One correction factor that may need to be considered is binaural summation effects (Behavioural: Hirsch, 1948a; 1948b). The present study applied masking binaurally, which is not commonly done clinically. Thus, the EMLs may be slightly higher than they could be when masking is done monaurally if binaural summation is a factor at the level of the brainstem.

3.2 Amplitude and Latency

For adult amplitudes, there were significant decreases in wave V amplitudes when the masker level increased for 500 and 2000 Hz. Although 500 Hz at 30 dB nHL did not yield statistically significant decreases in amplitude with increased masker, the pattern of results was consistent with the other levels at other frequencies. Adult wave V latencies increased significantly as masking levels increased at 500 Hz, but not for 2000 Hz, although, the trend observed was that latency increased as masking level increases. The findings are consistent with what was expected for masked responses.

Infant amplitudes significantly decreased with increased masker level in both frequencies at infant normal maximum levels. Significant decreases in amplitude was found when comparing ipsilateral vs contralateral channels for 500 Hz, but not for 2000 Hz, a pattern consistent with findings by Foxe and Stapells (1993). Infant wave V latencies increased with

increased masker level most significantly for the 500-Hz stimulus; no significant difference was found for 2000 Hz. This is consistent with the pattern found by Burkard and Hecox (1983), in which latency shifts were larger in lower frequencies.

As discussed earlier, ipsilateral-contralateral asymmetries frequently help the clinician ascertain the laterality of the responding cochlea to the ABR stimulus, as ipsilateral wave V amplitudes and latencies are larger and earlier, respectively, than their contralateral counterparts (Edwards, Durieux-Smith & Picton, 1985; Stapells, 1989; Stapells & Ruben, 1989; Stapells & Mosseri, 1991; Foxe & Stapells, 1993; Small & Stapells, 2008b). If the contralateral channel yields the larger and earlier wave V response, then it is the cochlea contralateral to the origin of the BC stimulus that produced the response, and a sensory loss is present in the test cochlea (Stapells, 1989; Sininger & Hyde, 2009). Clinically, particularly at low BC ABR stimulus levels, masking may not be warranted as infant unfused skull bones provide increased IA, especially for those younger than six months of age. However, once this advantage of greater IA is overcome by an elevation of threshold in one ear (e.g., unilateral sensorineural, bilateral conductive, or mixed hearing losses), or ipsilateral-contralateral asymmetries that are not easily identified by the clinician (ASSR; Small & Love, 2013), masking is needed to isolate the non-test ear.

3.3 Future Research

The present study found that only threshold and near-threshold BC tone pip stimuli at 500 and 2000 Hz could be safely masked. White noise was used as the present study's masker because it is the masker commonly available in clinical systems and, due to its broad frequency content, it ensures that a tone pip stimulus would be adequately masked. However, comfort and

hearing safety are important considerations when assessing clinical population, especially when high levels of masking are warranted. Future research could investigate a new masker that is just wide enough to be effective for BC tone pip stimuli but less intense than white noise.

The present study measured EMLs only from individuals with normal hearing. The recommended EMLs need to be assessed in future research in clinical populations to confirm that they are appropriate. Other ways to extend the present study include finding EMLs for 1000 and 4000 Hz stimuli. The EHDI programs in British Columbia and Ontario currently do not record BC ABRs at either 1000 or 4000 Hz in their standard protocol due to a lack of available clinical data (OIHP, 2008; BCEHP, 2012); however, there is interest in adding 4000-Hz BC responses to the protocol.

3.4 Conclusion

Normal-hearing infants require greater maximum EMLs than normal hearing adults for tone pip BC ABR stimuli. Maximum white noise levels needed to mask BC ABR stimuli in normal-hearing infants and adults when presented binaurally are as follows: Infants: 82 dB SPL for 500 Hz at 20 dB nHL, 72 and 82 dB SPL for 2000 Hz at 30 and 40 dB nHL, respectively; Adults: 72 and 82 dB SPL for 500 Hz at 20 and 30 dB nHL, respectively; 62, 72 and 82 dB SPL for 2000 Hz at 20, 30 and 40 dB nHL, respectively. Based on these findings, and assuming a minimum amount of BC IA of 10 dB for the signal presented to the infant test ear, the following monaural masking levels for the non-test ear are recommended clinically: 72 and 82 dB SPL for 500 Hz at 20 and 30 dB nHL, respectively; 62, 72 and 82 dB SPL for 2000 Hz at 30, 40 and 50 dB nHL, respectively.

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Appendices

Appendix A Individual Adult Data

A.1 Effective Masking Levels

Table A.1 Individual adult effective masking levels (dB SPL) for different bone-conducted stimulus frequency and level

ID	age (years)	500 Hz		2000 Hz	
		20 dBnHL	30 dBnHL	20 dBnHL	30 dBnHL
A6	30	52	62	---	---
A7	20	62	72	42	82
A8	18	62	82	62	62
A9	28	---	---	---	82
A10	23	62	77	---	---
A11	23	---	---	42	42
A13	25	---	---	52	62
A15	25	---	82	---	92
A17	22	---	---	52	62*
A18	54	72	---	52	62*
A19	21	---	---	---	62
A21	25	---	---	52	62*
A23	24	72	---	62	62
A25	21	---	---	62	---
A26	21	82	---	52	62
A27	20	62	72	52	62
A28	19	---	---	52	62
A29	20	---	---	---	62
A30	32	52	---	---	---
A32	21	72	82	52	62
Mean	24.60	65.00	75.57	52.77	65.13
SD	7.82	9.49	7.48	6.41	11.38
Min	18	52	62	42	42
Max	54	82	82	62	92
N	20	10	7	13	16

Notes:

(1) '---' denotes that data was not obtained

(2) grey-shaded value denotes data was determined by adding 10-dB SPL to the highest masker level that the individual still had a small response-present at

(3) '*' denotes the data was linearly obtained by using the effective masking level that was established in the same individual but for a different stimulus level of the same frequency

A.2 Amplitudes and Latencies

Table A.2 Individual adult ABR amplitude (μV) and latency (ms) responses in the ipsilateral channel, for different masking levels (dB SPL) of a 500-Hz bone-conducted stimuli presented at 20 dB nHL.

ID	Amplitude (μV)						Latency (ms)					
	unmasked	42	52	62	72	82	unmasked	42	52	62	72	82
A06	0.16	0.07	0.00	---	---	---	14.25	14.65	17.70	---	---	---
A07	0.23	0.18	0.07	CNE	---	---	15.35	16.65	20.10	CNE	---	---
A08	0.10	CNE	0.05	0.00	---	---	15.55	16.44	19.40	NR	---	---
A10	0.15	0.11	0.03	0.00	---	---	17.15	17.95	18.10	NR	---	---
A15	0.21	---	0.13	---	0.21	---	13.60	---	14.55	---	14.15	---
A18	0.09	0.11	0.10	0.04	0.00	---	17.20	17.00	20.85	22.00	NR	---
A23	0.10	---	0.09	0.05	0.00	---	18.05	---	17.95	17.90	NR	---
A26	0.34	---	0.11	0.04	0.09	0.00	13.35	---	14.70	15.35	16.60	NR
A27	0.23	0.21	0.07	0.00	---	---	13.80	15.20	17.40	NR	---	---
A28	0.21	---	---	CNE	---	---	13.15	---	---	CNE	---	---
A30	0.12	0.09	0.00	---	---	---	16.30	17.20	17.70	---	---	---
A32	0.22	---	0.13	0.08	0.00	---	13.30	---	16.25	16.40	NR	---
Mean	0.18	0.13	0.07	0.03	0.06	0.00	15.09	16.44	17.70	17.91	15.38	---
SD	0.07	0.05	0.05	0.03	0.09	---	1.75	1.15	2.00	2.92	1.73	---
Min	0.09	0.07	0.00	0.00	0.00	0.00	13.15	14.65	14.55	15.35	14.15	0.00
Max	0.34	0.21	0.13	0.08	0.21	0.00	18.05	17.95	20.85	22.00	16.60	0.00
N	12	6	11	7	5	1	12	7	11	4	2	0

Notes:

(1) '---' denotes that data was not obtained for this individual

(2) CNE denotes 'could not evaluate'

(3) NR denotes 'no response'

(4) grey-shaded value denotes data was obtained by using mean latencies for that masker level (dB SPL); occurs only when $N \geq 5$ with responses present (if $N < 5$, NR is used)

Table A.3 Individual adult ABR amplitude (μV) and latency (ms) responses in the ipsilateral channel, for different masking levels (dB SPL) of a 500-Hz bone-conducted stimuli presented at 30 dB nHL.

ID	Amplitude (μV)							Latency (ms)						
	unmasked	42	52	62	72	77	82	unmasked	42	52	62	72	77	82
A05	0.74	---	0.54	---	0.47	---	<i>CNE</i>	13.10	---	14.25	---	13.35	---	<i>CNE</i>
A06	0.15	---	0.07	0.00	---	---	---	12.40	---	15.30	17.15	---	---	---
A07	0.20	---	0.22	0.08	0.00	---	---	14.65	---	16.40	18.45	<i>NR</i>	---	---
A08	0.12	---	---	0.08	0.07	---	0.00	14.10	---	---	15.65	16.80	---	<i>NR</i>
A10	0.40	0.23	---	0.12	---	0.00	---	14.70	15.10	---	20.75	---	<i>NR</i>	---
A15	0.31	---	0.18	---	0.07	---	---	11.50	---	13.95	---	15.90	---	---
A27	0.27	---	0.17	0.06	0.00	---	0.00	12.30	---	15.35	15.45	---	---	<i>NR</i>
A32	0.29	---	---	0.06	0.07	---	<i>CNE</i>	13.20	---	---	15.25	15.15	---	<i>CNE</i>
Mean	0.31	0.23	0.24	0.07	0.11	0.00	0.00	13.24	15.10	15.05	17.12	15.30	---	---
SD	0.20	---	0.18	0.04	0.18	---	0.00	1.16	---	0.98	2.16	1.46	---	---
Min	0.12	0.23	0.07	0.00	0.00	0.00	0.00	11.50	15.10	13.95	15.25	13.35	0.00	0.00
Max	0.74	0.23	0.54	0.12	0.47	0.00	0.00	14.70	15.10	16.40	20.75	16.80	0.00	0.00
N	8	1	5	6	6	1	2	8	1	5	6	4	0	0

Notes:

- (1) '---' denotes that data was not obtained for this individual
- (2) CNE denotes 'could not evaluate'
- (3) NR denotes 'no response'

Table A.4 Individual adult ABR amplitude (μV) and latency (ms) responses in the ipsilateral channel, for different masking levels (dB SPL) of a 2000-Hz bone-conducted stimuli presented at 20 dB nHL.

ID	Amplitude (μV)									Latency (ms)								
	unmask	32	37	42	52	57	62	72	82	unmask	32	37	42	52	57	62	72	82
A07	0.23	---	0.07	0.00	---	---	---	---	---	11.20	---	11.40	10.50	---	---	---	---	---
A08	0.14	---	---	0.08	0.09	0.04	0.00	---	---	11.00	---	---	12.70	10.40	10.95	NR	---	---
A11	0.28	0.04	---	0.00	---	---	---	---	---	7.75	9.45	---	10.50	---	---	---	---	---
A13	0.14	---	---	0.04	0.00	---	---	---	---	10.20	---	---	10.30	NR	---	---	---	---
A15	0.64	---	---	0.25	CNE	---	0.00	---	---	9.25	---	---	9.40	11.95	---	NR	---	---
A17	0.10	---	---	0.05	0.00	---	---	---	---	9.95	---	---	10.10	NR	---	---	---	---
A18	0.17	---	---	0.06	0.00	---	0.00	0.00	---	11.50	---	---	10.05	NR	---	NR	NR	---
A21	0.22	0.11	---	0.04	0.00	---	---	---	---	10.40	10.70	---	10.95	NR	---	---	---	---
A23	0.34	0.16	---	0.06	0.08	---	0.00	---	---	12.40	13.05	---	13.65	13.50	---	NR	---	---
A25	0.26	---	---	0.08	0.06	---	---	---	---	10.90	---	---	10.50	13.55	---	---	---	---
A26	0.18	---	---	0.10	0.00	---	---	---	---	9.30	---	---	9.35	NR	---	---	---	---
A27	0.31	---	---	0.07	0.00	---	---	---	---	10.25	---	---	10.05	NR	---	---	---	---
A28	0.20	---	---	0.04	0.00	---	---	---	---	10.30	---	---	10.55	NR	---	---	---	---
A32	0.18	---	---	0.06	NR	---	---	---	---	9.90	---	---	10.60	NR	---	---	---	---
Mean	0.24	0.10	0.07	0.07	0.02	0.04	0.00	0.00	---	10.31	11.07	11.40	10.66	12.35	10.95	---	---	---
SD	0.13	0.06	---	0.06	0.04	---	0.00	---	---	1.12	1.83	---	1.17	1.50	---	---	---	---
Min	0.10	0.04	0.07	0.00	0.00	0.04	0.00	0.00	0.00	7.75	9.45	11.40	9.35	10.40	10.95	0.00	0.00	0.00
Max	0.64	0.16	0.07	0.25	0.09	0.04	0.00	0.00	0.00	12.40	13.05	11.40	13.65	13.55	10.95	0.00	0.00	0.00
N	14	3	1	14	10	1	4	1	0	14	3	1	14	4	1	0	0	0

Notes:

(1) '---' denotes that data was not obtained for this individual

(2) CNE denotes 'could not evaluate'

(3) NR denotes 'no response'

(4) grey-shaded value denotes data was obtained by using mean latencies for that masker level (dB SPL); occurs only when $N \geq 5$ with responses present (if $N < 5$, NR is used)

Table A.5 Individual adult ABR amplitude (μV) responses in the ipsilateral channel, for different masking levels (dB SPL) of a 2000-Hz bone-conducted stimuli presented at 30 dB nHL.

ID	Amplitude (μV)									
	unmasked	22	32	42	52	57	62	72	77	82
A07	0.20	---	---	---	0.08	---	---	0.05	---	---
A08	0.18	---	---	0.14	0.09	0.07	0.00	---	---	---
A09	0.26	---	---	---	---	---	0.05	---	CNE	---
A11	0.26	0.25	0.18	0.00	---	---	---	---	---	---
A13	0.31	---	---	---	0.03	---	0.00	---	---	---
A15	0.56	---	---	---	0.11	---	0.08	---	---	0.12
A17	0.22	---	---	0.21	CNE	---	CNE	CNE	---	---
A18	0.14	---	---	0.13	0.09	---	CNE	0.00	---	---
A19	0.21	---	---	0.10	0.03	---	0.00	0.00	---	---
A21	0.34	---	---	0.13	CNE	---	0.00	---	---	---
A23	0.58	---	---	0.23	0.05	---	0.00	---	---	---
A26	0.21	---	---	0.28	0.08	---	0.00	---	---	---
A27	0.51	---	---	0.26	0.07	---	0.00	---	---	---
A28	0.24	---	---	---	0.11	---	0.00	---	---	---
A29	0.37	---	---	0.29	0.14	---	0.00	---	---	---
A32	0.31	---	---	0.28	0.09	---	0.00	---	---	---
Mean	0.31	0.25	0.18	0.19	0.08	0.07	0.01	0.02	---	0.12
SD	0.14	---	---	0.09	0.03	---	0.03	0.03	---	---
Min	0.14	0.25	0.18	0.00	0.03	0.07	0.00	0.00	0.00	0.12
Max	0.58	0.25	0.18	0.29	0.14	0.07	0.08	0.05	0.00	0.12
N	16	1	1	11	12	1	12	3	0	1

Notes:

(1) '---' denotes that data was not obtained for this individual

(2) CNE denotes 'could not evaluate'

Table A.6 Individual adult ABR latency (ms) responses in the ipsilateral channel, for different masking levels (dB SPL) of a 2000-Hz bone-conducted stimuli presented at 30 dB nHL.

ID	Latency (ms)									
	unmasked	22	32	42	52	57	62	72	77	82
A07	10.50	---	---	---	11.70	---	---	11.45	---	<i>CNE</i>
A08	10.50	---	---	9.00	9.60	9.35	<i>NR</i>	---	---	---
A09	10.80	---	---	---	---	---	12.75	---	<i>CNE</i>	---
A11	10.55	10.20	9.95	9.84	---	---	---	---	---	---
A13	11.45	---	---	---	10.70	---	<i>NR</i>	---	---	---
A15	8.90	---	---	---	9.80	---	9.40	---	---	10.00
A17	9.75	---	---	9.55	9.23	---	<i>NR</i>	11.45	---	---
A18	11.25	---	---	10.50	10.70	---	<i>NR</i>	<i>NR</i>	---	---
A19	10.05	---	---	10.50	10.85	---	<i>NR</i>	11.45	---	---
A21	9.55	---	---	9.70	9.23	---	<i>NR</i>	---	---	---
A23	10.55	---	---	11.40	12.90	---	<i>NR</i>	---	---	---
A26	8.50	---	---	9.05	9.35	---	<i>NR</i>	---	---	---
A27	9.50	---	---	9.75	9.45	---	<i>NR</i>	---	---	---
A28	9.55	---	---		9.45	---	<i>NR</i>	---	---	---
A29	9.15	---	---	9.35	10.05	---	<i>NR</i>	---	---	---
A32	9.20	---	---	9.60	9.75	---	<i>NR</i>	---	---	---
Mean	9.98	10.20	9.95	9.84	10.20	9.35	11.08	11.45	---	10.00
SD	0.85	---	---	0.71	1.07	---	2.37	0.00	---	---
Min	8.50	10.20	9.95	9.00	9.23	9.35	9.40	11.45	0.00	10.00
Max	11.45	10.20	9.95	11.40	12.90	9.35	12.75	11.45	0.00	10.00
N	16	1	1	11	14	1	2	3	0	1

Notes:

- (1) '---' denotes that data was not obtained for this individual (2) CNE denotes 'could not evaluate' (3) NR denotes 'no response'
(4) grey-shaded value denotes data was obtained by using mean latencies for that masker level (dB SPL); occurs only when $N \geq 5$ with responses present (if $N < 5$, *NR* is used)

Appendix B Individual Infant Data

B.1 Effective Masking Levels

Table A.7 Individual infant effective masking levels (dB SPL) for different bone-conducted stimulus frequency and level

ID	age (weeks)	500 Hz		2000 Hz	
		20 dB nHL	30 dB nHL	30 dB nHL	40 dB nHL
I01	8	72	82	---	---
I06	13	---	---	62*	72
I07	9	---	---	72	82
I08	17	82	92	52	72
I10	47	72	---	---	---
I11	47	---	---	72	72
I12	37	---	---	72	---
I13	25	---	---	62	---
I14	30	82	---	---	---
I15	12	82	---	62	---
I16	6	72	---	52	---
I17	13	82	---	62	---
I19	13	---	---	62	---
I20	43	72	---	---	---
I21	47	---	---	62	---
I22	11	82	---	52	---
I23	32	82	---	---	---
I24	34	92	---	82	---
I25	21	82	---	72	---
I26	8	82	---	62	---
Mean	23.65	79.69	87.00	64.00	74.50
SD	14.71	5.99	7.07	8.62	5.00
Min	6	72	82	52	72
Max	47	92	92	82	82
N	20	13	2	15	4

Notes:

- (1) '---' denotes that effective masking level was not obtained
- (2) grey-shaded value denotes effective masking level was determined by adding 10-dB SPL to the highest masker level that the individual still had a small response-present at
- (3) '*' denotes the effective masking level was linearly obtained by using the effective masking level that was established in the same individual but for a different stimulus level of the same frequency

B.2 Amplitudes

Table A.8 Individual infant ABR amplitude responses (μV) in the ipsilateral/contralateral channels, for different masking levels (dB SPL) of a 500-Hz bone-conducted stimuli presented at 20 dB nHL.

ID	Ipsilateral Channel						Contralateral Channel					
	unmasked	42	52	62	72	82	unmasked	42	52	62	72	82
I01	0.30	---	0.13	0.05	0.00	---	0.29	---	0.14	0.00	0.00	---
I07	0.25	---	0.18	0.14	0.11	---	0.17	---	0.08	0.21	0.22	---
I08	0.14	0.09	0.08	0.05	0.07	<i>CNE</i>	0.13	<i>CNE</i>	<i>CNE</i>	0.04	0.05	0.00
I10	0.55	---	0.12	0.18	0.00	---	0.23	---	0.11	<i>CNE</i>	0.00	---
I13	0.15	---	0.12	<i>CNE</i>	<i>CNE</i>	---	0.12	---	0.06	<i>CNE</i>	<i>CNE</i>	---
I14	0.26	---	0.21	0.10	0.11	0.00	0.13	---	0.09	0.00	0.00	0.15
I15	0.28	---	0.11	0.11	0.10	0.00	0.17	---	0.07	0.09	0.00	---
I16	0.36	0.11	0.10	0.04	0.00	<i>CNE</i>	0.14	0.14	0.12	0.04	0.00	0.00
I17	0.24	0.09	0.13	0.08	0.06	0.00	0.28	<i>CNE</i>	0.16	0.07	0.08	<i>CNE</i>
I18	0.19	---	0.11	0.05	<i>CNE</i>	---	0.14	---	0.10	0.06	<i>CNE</i>	---
I20	0.23	---	0.16	0.12	0.00	---	0.15	---	0.12	<i>CNE</i>	<i>CNE</i>	---
I21	0.18	---	0.15	0.15	---	---	0.29	---	0.18	0.13	---	---
I22	0.29	---	0.27	0.18	0.06	0.00	0.13	---	0.13	0.08	0.07	0.00
I23	0.19	---	---	0.23	0.09	0.00	0.20	---	---	0.17	0.00	<i>CNE</i>
I24	0.25	---	0.19	0.16	0.15	0.17	0.10	---	0.09	0.07	<i>CNE</i>	0.00
I25	0.36	---	0.15	0.14	0.09	0.00	0.18	---	0.15	0.10	0.00	0.00
I26	0.15	---	0.16	0.07	0.06	0.00	0.06	---	0.12	0.07	0.00	0.00
Mean	0.26	0.10	0.15	0.12	0.06	0.02	0.17	0.14	0.11	0.08	0.04	0.02
SD	0.10	0.01	0.05	0.06	0.05	0.06	0.07	---	0.03	0.06	0.07	0.06
Min	0.14	0.09	0.08	0.04	0.00	0.00	0.06	0.14	0.06	0.00	0.00	0.00
Max	0.55	0.11	0.27	0.23	0.15	0.17	0.29	0.14	0.18	0.21	0.22	0.15
N	17	3	16	16	14	8	17	1	15	14	12	7

Notes:

(1) '---' denotes that data was not obtained for this individual

(2) CNE denotes 'could not evaluate'

Table A.9 Individual infant ABR amplitude responses (μV) in the ipsilateral/contralateral channels, for different masking levels (dB SPL) of a 500-Hz bone-conducted stimuli presented at 30 dB nHL.

ID	Ipsilateral Channel						Contralateral Channel					
	unmasked	42	52	62	72	82	unmasked	42	52	62	72	82
I01	0.25	---	0.26	0.13	0.06	0.00	0.31	---	0.22	0.15	0.05	0.00
I03	0.59	---	0.28	---	<i>CNE</i>	---	0.27	---	0.11	---	<i>CNE</i>	---
I08	0.27	---	0.20	---	0.04	<i>CNE</i>	0.11	---	<i>CNE</i>	---	0.00	<i>CNE</i>
I10	0.35	---	---	---	0.10	---	0.21	---	---	---	0.09	---
I11	0.28	---	---	0.27	0.27	0.07	0.27	---	---	0.17	<i>CNE</i>	<i>CNE</i>
I13	0.13	---	---	0.14	0.07	0.09	0.12	---	---	0.12	<i>CNE</i>	<i>CNE</i>
Mean	0.31	---	0.25	0.18	0.11	0.05	0.22	---	---	---	---	---
SD	0.15	---	0.04	0.08	0.09	0.05	0.08	---	0.08	0.03	0.05	---
Min	0.13	0.00	0.20	0.13	0.04	0.00	0.11	0.00	0.11	0.12	0.00	0.00
Max	0.59	0.00	0.28	0.27	0.27	0.09	0.31	0.00	0.22	0.17	0.09	0.00
N	6	0	3	3	5	3	6	0	2	3	3	1

Notes:

(1) '---' denotes that data was not obtained for this individual

(2) CNE denotes 'could not evaluate'

Table A.10 Individual infant ABR amplitude responses (μV) in the ipsilateral/contralateral channels, for different masking levels (dB SPL) of a 2000-Hz bone-conducted stimuli presented at 30 dB nHL.

ID	Ipsilateral Channel							Contralateral Channel						
	unmask	32	42	52	62	72	82	unmask	32	42	52	62	72	82
I01	0.30	---	---	0.09	---	0.00	0.00	0.30	---	---	0.05	---	0.00	0.00
I02	0.19	---	0.07	CNE	0.00	---	---	0.22	---	0.04	0.00	0.00	---	---
I06	0.24	---	---	0.09	CNE	CNE	---	0.19	---	---	CNE	CNE	0.00	---
I07	0.37	---	---	0.16	0.25	0.00	---	0.19	---	---	CNE	0.05	0.05	---
I08	0.32	---	0.08	0.00	0.00	---	---	0.31	---	0.06	0.00	0.00	---	---
I09	0.19	0.13	0.05	CNE	---	---	---	0.11	0.05	0.00	CNE	---	---	---
I10	0.27	---	---	0.10	CNE	CNE	---	0.30	---	---	0.23	0.18	0.13	---
I11	0.35	---	---	0.05	0.05	0.00	---	0.15	---	---	0.03	0.07	CNE	---
I12	0.35	---	---	0.09	0.05	0.00	---	0.16	---	---	CNE	0.08	0.00	---
I13	0.24	---	---	0.06	0.00	---	---	0.19	---	---	0.00	0.00	---	---
I15	0.16	---	---	0.07	0.00	0.00	---	0.00	---	---	0.00	0.00	0.00	---
I16	0.15	---	0.06	0.00	0.00	---	---	0.12	---	0.09	CNE	0.00	---	---
I17	0.16	---	---	0.07	0.00	---	---	0.20	---	---	0.06	0.00	---	---
I19	0.13	---	---	0.05	0.00	---	---	0.10	---	---	0.00	0.00	---	---
I20	0.41	---	---	---	CNE	---	---	0.32	---	---	---	CNE	---	---
I21	0.23	---	0.17	0.08	0.00	---	---	0.26	---	0.12	0.09	0.00	---	---
I22	0.27	---	0.09	0.00	0.00	---	---	0.19	---	0.06	0.00	0.00	---	---
I24	0.30	---	---	0.31	0.16	0.06	0.00	0.33	---	---	0.16	0.11	0.08	0.00
I25	0.38	---	---	---	0.07	0.00	---	0.49	---	---	---	0.06	CNE	---
I26	0.09	---	0.06	0.05	0.00	---	---	0.10	---	EXC	EXC	EXC	---	---
Mean	0.26	0.13	0.08	0.08	0.04	0.01	0.00	0.21	0.05	0.06	0.05	0.04	0.04	0.00
SD	0.09	---	0.04	0.07	0.07	0.02	0.00	0.11	---	0.04	0.07	0.05	0.05	0.00
Min	0.09	0.13	0.05	0.00	0.00	0.00	0.00	0.00	0.05	0.00	0.00	0.00	0.00	0.00
Max	0.41	0.13	0.17	0.31	0.25	0.06	0.00	0.49	0.05	0.12	0.23	0.18	0.13	0.00
N	20	1	7	16	15	7	2	20	1	6	12	15	7	2

Notes:

- (1) '---' denotes that data was not obtained for this individual (2) CNE denotes 'could not evaluate'
(3) EXC denotes data was excluded due to loose insert earphone only in contralateral channel

Table A.11 Individual infant ABR amplitude responses (μV) in the ipsilateral/contralateral channels, for different masking levels (dB SPL) of a 2000-Hz bone-conducted stimuli presented at 40 dB nHL.

ID	Ipsilateral Channel						Contralateral Channel					
	unmasked	42	52	62	72	82	unmasked	42	52	62	72	82
I01	0.37	---	0.22	---	---	---	0.33	---	0.14	---	---	---
I06	0.22	---	0.10	0.05	0.00	---	0.23	---	<i>CNE</i>	<i>CNE</i>	<i>CNE</i>	---
I07	0.31	---	0.19	0.09	0.09	0.00	0.19	---	<i>CNE</i>	<i>CNE</i>	<i>CNE</i>	0.00
I08	0.32	0.18	0.13	0.07	0.00	---	0.25	0.11	0.04	0.00	0.00	---
I09	0.14	0.18	<i>CNE</i>	0.00	---	---	0.18	0.20	0.16	<i>CNE</i>	---	---
I11	0.33	0.23	0.11	0.10	0.00	<i>CNE</i>	0.38	0.25	0.12	0.18	<i>CNE</i>	<i>CNE</i>
I14	0.52	0.35	---	---	---	---	0.28	<i>CNE</i>	---	---	---	---
I15	0.23	---	0.10	<i>CNE</i>	---	---	0.12	---	<i>CNE</i>	0.04	---	---
Mean	0.31	0.24	0.14	0.06	0.02	0.00	0.25	0.19	0.12	0.07	0.00	0.00
SD	0.11	0.08	0.05	0.04	0.05	---	0.08	0.07	0.05	0.09	---	---
Min	0.14	0.18	0.10	0.00	0.00	0.00	0.12	0.11	0.04	0.00	0.00	0.00
Max	0.52	0.35	0.22	0.10	0.09	0.00	0.38	0.25	0.16	0.18	0.00	0.00
N	8	4	6	5	4	1	8	3	4	3	1	1

Notes:

(1) '---' denotes that data was not obtained for this individual

(2) *CNE* denotes 'could not evaluate'

B.3 Latencies

Table A.12 Individual infant ABR latency responses (ms) in the ipsilateral/contralateral channels, for different masking levels (dB SPL) of a 500-Hz bone-conducted stimuli presented at 20 dB nHL.

ID	Ipsilateral Channel						Contralateral Channel					
	unmasked	42	52	62	72	82	unmasked	42	52	62	72	82
I01	13.40	---	15.55	16.95	15.96	---	13.60	---	15.75	16.68	NR	---
I06	---	---	---	---	---	---	---	---	---	16.68	---	---
I07	13.35	---	14.60	14.60	14.85	---	13.35	---	14.90	15.30	15.50	---
I08	13.25	13.25	14.30	14.55	15.55	NR	14.85	CNE	CNE	18.20	18.80	NR
I10	12.50	---	14.75	16.20	15.96	---	13.80	---	15.10	CNE	NR	---
I13	13.55	---	16.10	CNE	CNE	---	14.45	---	16.30	CNE	CNE	---
I14	14.40	---	15.10	16.55	16.55	NR	14.40	---	15.00	16.68	NR	16.10
I15	12.20	---	12.40	14.10	15.15	NR	14.05	---	16.55	16.70	NR	---
I16	12.80	14.65	15.55	17.30	15.96	CNE	13.75	14.90	15.55	17.05	NR	NR
I17	13.95	15.20	15.30	15.95	18.20	NR	14.85	CNE	18.05	19.45	20.15	CNE
I18	14.00	---	13.95	15.60	CNE	---	15.20	---	17.05	17.20	CNE	---
I20	12.90	---	13.75	17.60	15.96	---	14.10	---	17.60	CNE	CNE	---
I21	14.75	---	16.25	16.65	---	---	14.75	---	16.50	17.30	---	---
I22	12.85	---	14.20	15.10	15.55	NR	16.85	---	17.45	18.00	19.30	NR
I23	13.85	---	---	15.60	16.95	NR	13.85	---	---	15.60	NR	CNE
I24	12.60	---	12.90	13.55	13.55	13.55	12.75	---	12.90	13.05	CNE	NR
I25	12.55	---	14.85	15.00	16.85	NR	13.30	---	15.20	16.35	NR	NR
I26	13.35	---	15.25	15.45	16.35	NR	13.75	---	15.65	15.90	NR	NR
Mean	13.31	14.37	14.68	15.67	15.96	13.55	14.21	14.90	15.97	16.68	18.44	16.10
SD	0.71	1.01	1.07	1.16	1.09	---	0.93	---	1.32	1.45	2.04	---
Min	12.20	13.25	12.40	13.55	13.55	13.55	12.75	14.90	12.90	13.05	15.50	16.10
Max	14.75	15.20	16.25	17.60	18.20	13.55	16.85	14.90	18.05	19.45	20.15	16.10
N	17	3	16	16	14	1	17	1	15	15	4	1

Notes:

- (1) '---' denotes that data was not obtained for this individual (2) CNE denotes 'could not evaluate' (3) NR denotes 'no response'
(4) grey-shaded value denotes data was obtained by using mean latencies for that masker level (dB SPL); occurs only when $N \geq 5$ with responses present (if $N < 5$, NR is used)

Table A.13 Individual infant ABR latency responses (ms) in the ipsilateral/contralateral channels, for different masking levels (dB SPL) of a 500-Hz bone-conducted stimuli presented at 30 dB nHL.

ID	Ipsilateral Channel						Contralateral Channel					
	unmasked	42	52	62	72	82	unmasked	42	52	62	72	82
I01	12.75	---	14.40	15.15	17.10	<i>NR</i>	12.75	---	15.25	15.10	15.95	<i>NR</i>
I03	13.20	---	12.70	---	<i>CNE</i>	---	13.35	---	15.75	---	<i>CNE</i>	---
I08	12.15	---	13.40	---	17.60	<i>CNE</i>	12.55	---	<i>CNE</i>	---	<i>NR</i>	<i>CNE</i>
I10	12.80	---	---	---	13.80	---	13.80	---	---	---	16.55	---
I11	12.40	---	---	12.90	12.90	16.35	14.25	---	---	14.90	<i>CNE</i>	<i>CNE</i>
I13	13.75	---	---	14.35	17.50	18.95	13.85	---	---	12.10	<i>CNE</i>	<i>CNE</i>
Mean	12.84	---	13.50	14.13	15.78	17.65	13.43	---	15.50	14.03	16.25	---
SD	0.57	---	0.85	1.14	2.25	1.84	0.67	---	0.35	1.68	0.42	---
Min	12.15	0.00	12.70	12.90	12.90	16.35	12.55	0.00	15.25	12.10	15.95	0.00
Max	13.75	0.00	14.40	15.15	17.60	18.95	14.25	0.00	15.75	15.10	16.55	0.00
N	6	0	3	3	5	2	6	0	2	3	2	0

Notes:

- (1) '---' denotes that data was not obtained for this individual
- (2) *CNE* denotes 'could not evaluate'
- (3) *NR* denotes 'no response'

Table A.14 Individual infant ABR latency responses (ms) in the ipsilateral/contralateral channels, for different masking levels (dB SPL) of a 2000-Hz bone-conducted stimuli presented at 30 dB nHL.

ID	Ipsilateral Channel							Contralateral Channel						
	unmask	32	42	52	62	72	82	unmask	32	42	52	62	72	82
I01	9.50	---	---	10.45	---	NR	NR	10.80	---	---	11.15	---	NR	NR
I02	9.30	---	10.10	CNE	10.71	---	---	9.15	---	10.55	10.78	11.24	---	---
I06	9.80	---	---	16.15	CNE	CNE	---	11.50	---	---	CNE	CNE	NR	---
I07	8.75	---	---	10.25	10.25	NR	---	10.95	---	---	CNE	11.95	11.60	---
I08	10.15	---	10.50	10.96	10.71	---	---	10.15	---	11.40	10.78	11.24	---	---
I09	10.05	9.75	10.70	CNE	---	---	---	10.85	11.60	NR	CNE	---	---	---
I10	9.70	---	---	10.35	CNE	CNE	---	9.80	---	---	10.25	10.35	10.20	---
I11	10.35	---	---	10.35	11.15	NR	---	10.15	---	---	10.10	10.45	CNE	---
I12	8.80	---	---	8.90	11.05	NR	---	10.00	---	---	CNE	13.55	NR	---
I13	9.80	---	---	11.10	10.71	---	---	11.15	---	---	10.78	11.24	---	---
I15	10.45	---	---	10.95	10.71	NR	---	10.50	---	---	10.78	11.24	NR	---
I16	10.95	---	11.00	10.96	10.71	---	---	11.70	---	11.60	CNE	11.24	---	---
I17	10.20	---	---	10.55	10.71	---	---	10.75	---	---	11.60	11.24	---	---
I19	10.25	---	---	11.50	10.71	---	---	10.75	---	---	10.78	11.24	---	---
I20	10.15	---	---	---	CNE	---	---	10.10	---	---	---	CNE	---	---
I21	11.10	---	10.20	11.10	10.71	---	---	11.15	---	11.65	11.65	11.24	---	---
I22	9.60	---	10.50	10.96	10.71	---	---	10.40	---	10.55	10.78	11.24	---	---
I24	9.70	---	---	9.80	9.90	10.20	NR	9.80	---	---	9.90	10.15	10.50	NR
I25	9.35	---	---	---	11.20	NR	---	9.45	---	---	---	11.00	CNE	---
I26	10.60	---	11.05	11.00	NR	---	---	10.95	---	EXC	EXC	EXC	---	---
Mean	9.93	9.75	10.58	10.96	10.71	10.20	---	10.50	11.60	11.15	10.78	11.24	10.77	---
SD	0.63	---	0.36	1.52	0.33	---	---	0.67	---	0.56	0.53	0.78	0.74	---
Min	8.75	9.75	10.10	8.90	9.90	10.20	0.00	9.15	11.60	10.55	9.90	10.15	10.20	0.00
Max	11.10	9.75	11.05	16.15	11.20	10.20	0.00	11.70	11.60	11.65	11.65	13.55	11.60	0.00
N	20	1	7	16	14	1	0	20	1	5	12	15	3	0

Notes: (1) '---' denotes that data was not obtained for this individual (2) CNE denotes 'could not evaluate' (3) NR denotes 'no response'
(4) EXC denotes data was excluded due to loose insert earphone only in one channel
(5) grey-shaded value denotes data was obtained by using mean latencies for that masker level (dB SPL); occurs only when $N \geq 5$ with responses present (if $N < 5$, NR is used)

Table A.15 Individual infant ABR latency responses (ms) in the ipsilateral/contralateral channels, for different masking levels (dB SPL) of a 500-Hz bone-conducted stimuli presented at 30 dB nHL.

ID	Ipsilateral Channel						Contralateral Channel					
	unmasked	42	52	62	72	82	unmasked	42	52	62	72	82
I01	12.75	---	14.40	15.15	17.10	<i>NR</i>	12.75	---	15.25	15.10	15.95	<i>NR</i>
I03	13.20	---	12.70	---	<i>CNE</i>	---	13.35	---	15.75	---	<i>CNE</i>	---
I08	12.15	---	13.40	---	17.60	<i>CNE</i>	12.55	---	<i>CNE</i>	---	<i>NR</i>	<i>CNE</i>
I10	12.80	---	---	---	13.80	---	13.80	---	---	---	16.55	---
I11	12.40	---	---	12.90	12.90	16.35	14.25	---	---	14.90	<i>CNE</i>	<i>CNE</i>
I13	13.75	---	---	14.35	17.50	18.95	13.85	---	---	12.10	<i>CNE</i>	<i>CNE</i>
Mean	12.84	---	13.50	14.13	15.78	17.65	13.43	---	15.50	14.03	16.25	---
SD	0.57	---	0.85	1.14	2.25	1.84	0.67	---	0.35	1.68	0.42	---
Min	12.15	0.00	12.70	12.90	12.90	16.35	12.55	0.00	15.25	12.10	15.95	0.00
Max	13.75	0.00	14.40	15.15	17.60	18.95	14.25	0.00	15.75	15.10	16.55	0.00
N	6	0	3	3	5	2	6	0	2	3	2	0

Notes:

- (1) '---' denotes that data was not obtained for this individual
- (2) *CNE* denotes 'could not evaluate'
- (3) *NR* denotes 'no response'