Observations on Temporal Aspects of Bone-Conduction Clicks: Real Head Measurements

John D. Durrant*
Rick Hyre*

Abstract
To further elucidate nuances of bone-conduction (BC) stimulation, particularly as they may pertain to BC-elicited auditory brainstem responses (ABRs), real head measurements were made of vibratory responses to BC clicks. A miniature accelerometer was held firmly against the skull near a bone vibrator applied to the mastoid, to the opposite mastoid, and to the forehead. Measurements also were made with the vibrator applied to the forehead and the accelerometer placed on a mastoid. The measured vibrations were compared among conditions within and across subjects. The results demonstrate that vibration picked up in the immediate vicinity of the vibrator, roughly mimics the temporal and spectral characteristics of the click observed on an artificial mastoid. However, probing at sites remote to the bone vibrator suggested the introduction of a propagation-like delay as well as low-pass filtering. These findings support observations of previous researchers who demonstrated phase differences between vibrations recorded at different points on the skull, further demonstrating the complexities of skull vibration. Latency differences of ABR responses obtained with forehead versus mastoid placements, for example, cannot be attributed merely to the difference in efficiency between sites of stimulation demonstrated audiometrically. While the real head observations do not permit determination of the actual vibratory lag at the cochlea, they do permit the deduction that a comparable onset delay occurs in BC as in air-conduction stimulation via supraaural earphones.

Key Words: Accelerometer, auditory brainstem response (ABR), bone conduction, click stimuli

Evaluation of the auditory brainstem response (ABR) using bone-conducted stimulation has met with guarded interest. The major concern has been generated seemingly by the observation that, except in very young children (discussed below), the ABR elicited by bone-conduction (BC) clicks tends to have a longer latency than the ABR elicited by clicks produced by conventional audiometric earphones (Kavanaugh and Beardsley, 1979; Mauldin and Jerger, 1979; Cornacchia et al, 1983; Weber, 1983; Schwartz et al, 1985). The prevailing notion is that the BC click appears to be a low-pass-filtered version of the air-conduction (AC) click and, therefore, that ABR latency differences between modes of stimulation are entirely attributable to spectral differences in these stimuli.

The “low-pass” concept seems consistent with measured frequency response of bone vibrators versus earphones on their respective calibration couplers. These measurements suggest the bone vibrator to have mid-frequency resonance peaks and precipitous roll-off in response, yielding high-frequency output substantially below that demonstrated for earphones. Gorga and Thornton (1989), however, have questioned whether the effective high-frequency output of the bone vibrator is as deficient as previously thought and whether there are not other bases for the difference between BC and AC elicited ABRs. We recently reported observations on the effective relative frequency response of BC versus AC stimulation (Durrant and Hyre, in press) and found that the artificial mastoid appreciably underestimates the effective high-frequency output of the bone vibrator.
Bone conducted stimuli are thus expected to be under the influence of factors inherent to this mode of stimulation that go beyond apparent differences in frequency response characteristics of BC versus AC stimuli and among vibrator placement sites and that can affect the expression of the stimulus at the cochlea. Such factors naturally can contribute to latencies of BC-elicited ABRs. We report here observations of real-head accelerometer measurements of BC clicks undertaken to investigate the possible contribution of propagational factors that may help to better explain observed differences in BC- and AC-click elicited ABRs and differences in responses obtained with forehead versus mastoid vibrator placement.

**METHOD**

The subjects were 4 males and 3 females. The range of the subjects' ages was from 16 to 46 years. This project was approved for use of human subjects by the internal review board of The Eye & Ear Institute of Pittsburgh.

A miniature accelerometer (Brüel & Kjær 4375) was used for examining the response of the skull in situ (i.e., real head measurements). The signal from the accelerometer was conditioned via a charge amplifier (Brüel & Kjær 2651). In making the real head measurements, the bone vibrator, a modified Radioear B71 (see below), was held in place by a standard headband, whereas the accelerometer was held firmly against the skull by the experimenter. Consequently, loading from the experimenter's finger was likely to have occurred, as well as variability in coupling to the skull within and across subjects. To help minimize these variables, coupling was enhanced by encouraging the subject to maintain, by neck muscle resistance, a tightness of coupling such that the pressure of the transducer against the skull was just tolerable.

Noise/variability potentially introduced by supporting the accelerometer by hand was further reduced by the use of time-ensemble digital signal averaging. The number of stimulus repetitions per ensemble average equalled 1024 (two averages per condition were acquired). In general, variance is expected to be expressed, first, in the magnitude of the recorded responses. Magnitude, however, was not of interest, so response magnitude was normalized. (This is discussed in more detail below.) Measurement variability also is expected to be expressed in the frequency content of the recorded responses. This source of variability could not be teased out. Of additional concern is variability of the onset of the response, since we were particularly interested in temporal measurements. However, the ipsilaterally recorded vibratory responses, shown for all subjects in Figure 1, suggest negligible artifact of this type. Indeed, as demonstrated below (see Fig. 3), the initial cycle of vibration could be superimposed almost perfectly across all subjects.

For ipsilateral vibratory measurements on the mastoid, the accelerometer was held about
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1 cm diagonally posterior and inferior to the bone vibrator. This position permitted measurement reasonably close to the bone vibrator without the risk of direct contact. Other monitoring sites were the corresponding site on the contralateral mastoid and the center of the forehead. The center of the forehead also served as an alternative stimulation site. Both forehead stimulation/recording conditions were employed because we did not know, at the outset, what to expect of the possible influences of skull impedance on stimulation versus measurement at the different sites. Presumably, a given cochlea ought to receive vibration most directly related to (but not necessarily identical to) that of the ipsilateral mastoid. Considering clinical practice, however, the condition of bone vibrator on forehead and measurement at mastoid also was of interest. Given the possibility that simply placing and replacing the bone vibrator might introduce substantial variability, it seemed most prudent then to include the condition of vibrator on mastoid and accelerometer on forehead. In this way, comparisons between sites could be accomplished without movement of the bone vibrator. Comparison between forehead conditions thus permitted scrutiny of the vibrator replacement variable. Comparisons between the ipsilateral mastoid condition with placement and replacement of the vibrator permitted further scrutiny of this factor.

Click BC stimuli were generated by delivering a 100-microsecond pulse to a Radioear B71, presented at levels corresponding nominally to 70 dB nHL. Although this level represents a saturating drive level for the BC transducer, the measures of interest here were relative (i.e., differences between stimulus/measurement sites), and a sufficiently strong vibration was needed to obtain adequate dynamic ranges for the measurements. It should be noted that the miniature accelerometer provides excellent frequency response characteristics, but at the cost of relatively poor sensitivity. To compensate for the inherent inefficiency of the bone-conduction mode of stimulation (namely, 40 dB difference, with respect to conventional audiometric earphones), we used an additional stage of amplification between the earphone output of the evoked response test system (used for response stimulation and measurement) and the bone vibrator. This “add-on” amplifier stage also permitted frequency response equalization, wherein high-frequency emphasis was used to improve the signal-to-noise ratio of the measured response in the high frequencies. A high-pass filter was employed with a 12 dB/octave roll-off below 2 kHz. The B71 bone vibrator also was modified by removing the lead weight from the pole piece. It is the mass of this weight, for example, that makes the difference between the response characteristics of a B71 and a B72 (i.e., more mass in the B72, yielding more low-frequency output). This modification served to reduce the first resonant peak. The net result is illustrated in Figure 2 (uppermost panel) and served to produce a reference frequency response on the artificial mastoid (Brüel & Kjær 4930) that was reasonably flat from about 500 to 4000 Hz. As seen in Figure 2, the high-frequency-emphasized BC click was fairly “sharp” temporally, which seemed worthwhile for probing temporal features of vibrations elicited under the different stimulus/measurement conditions. It should be emphasized that the latter modifications were implemented for measurement purposes; the deductions drawn from these measurements are expected to be equally valid for BC stimuli generated by the unaltered B71 driven by an unequalized amplifier.

Analyses of the data were largely descriptive, based on averaging the test–retest trials for each condition (after inspection for reasonable reproducibility). Spectral analyses of the recorded vibratory responses were accomplished via the fast Fourier transform. It was also of interest to assess overall temporal differences between the vibratory responses at the different measurement/stimulus sites. For this purpose, the cross-correlation between two responses of interest were computed for lags of ±14 data
Figure 2. Vibration picked up in the immediate vicinity of the vibrator, that is recording from the ipsilateral mastoid, roughly followed the temporal and spectral characteristics of the click observed on the artificial mastoid, but with response characteristics more colored by resonances. Probing at sites remote to the bone vibrator suggested the introduction of a propagation-like delay and/or low-pass filtering.

These trends, as well as the similarities and differences across subjects and among conditions, are further illustrated in Figure 3, showing individual subjects' plots of vibratory responses probed at the ipsilateral mastoid, contralateral mastoid, and forehead. Test–retest waveforms were averaged together to improve the signal-to-noise ratio. Treating the ipsilaterally stimulated and recorded responses as best estimates of the vibratory input signal, the responses under this condition were used to

Figure 3 Vibratory responses recorded with the bone vibrator on the mastoid with the accelerometer on the ipsilateral mastoid (I), contralateral mastoid (C), and forehead (F). Ipsilaterally stimulated and recorded responses normalized (norm) to yield uniform peak-to-peak amplitudes across subjects, as in Figure 1. C and F tracings are amplified by a factor of 3 (denoted by vertical "calibration" bars) to aid visual inspection of these waveforms. All Ipsi. = all I waveforms overlaid.

RESULTS

Results from one subject, which characterize the "raw" data, test–retest variability, and trends of both spectral and temporal features of the recorded vibrations are presented in
reconcile effective click polarity and for normalization of the response amplitudes across subjects. For example, subject JF's responses were inverted in Figure 3. Maximal peak-to-peak magnitudes were used to calculate the normalized amplitudes of the responses, yielding peak amplitudes of ±0.5 and reasonably good overlay of all subjects' responses, as seen in the "All Ips." panel of Figure 3. As might be expected, the ipsilaterally recorded response was several or more times greater in amplitude than the other responses; the forehead responses were typically the weakest. More intriguing, was the typical delay of the remotely probed vibrations. The overall delays were roughly comparable between the mastoid and forehead. Using the ipsilaterally measured response as the reference and cross-correlation analyses, these delays ranged from 0.06 to 0.60 msec (median = 0.42 msec) for the contralateral mastoid and 0.48 to 0.72 msec (median = 0.48 msec) for the forehead. Except for two subjects under the contralateral mastoid condition (RH; JD) and one subject under the forehead conditions (JF), maximal cross-correlations were negative values. Thus, the best matches between waveforms across conditions generally required response inversion for best overlays, in addition to the lag adjustment.

With the bone vibrator applied to the forehead and recording from the mastoid, similar responses were obtained as those recorded vice versa. To facilitate direct comparisons, overlays of the vibratory responses for the two forehead recording/measurement conditions are provided in Figure 4. Note that recordings under this condition were obtained in only 6 subjects. The cross-correlation analyses demonstrated no differences in onset in two cases (MD; RH) and slightly greater delays (0.12–0.18 msec) in the remaining subjects. In only one of these subjects (SS) was the maximum correlation value negative (that is, requiring waveform inversion for best overall overlay of the two waveforms); the lag in this case was 0.12 msec.

Subject JF demonstrated the greatest discrepancies in waveform morphology between conditions. Despite the clear trend toward greater delays in vibratory response onset for the condition of bone vibrator on forehead, the observed lags still did not exceed those observed upon test–retest comparisons for the ipsilaterally stimulation/recording condition (0.00–0.18 msec). The test–retest results thus mitigate against significance of the differences in onset of the two forehead stimulus/recording conditions, suggesting them to be merely the result of procedural artifact. On the other hand, in no case did the "retest" waveform require inversion for best-fit overlay of the "test" waveform nor were there substantive changes in wave morphology. Regardless, the results clearly suggest a substantive forehead-to-mastoid delay, which is minimally dependent, in most subjects, upon the way that it is determined (i.e., bone vibrator on forehead and accelerometer on mastoid or vice versa). It also is interesting that, even when responses were normalized to the amplitude of the ipsilaterally recorded and stimulated vibratory responses, there was considerable variability in amplitude of the remotely probed responses across subjects.

**DISCUSSION**

These results support the notion that the modes of vibration of the plates of the skull contribute significantly to phase/temporal differences between sites of stimulation and/or measurement. Indeed, the differences between vibratory responses recorded under the conditions examined here seem attributable mostly to propagational delays, rather than just variations in response spectra between sites. In reference to eliciting a physiologic response, such as the ABR, propagational delays contribute to the absolute latencies of the waves, just as the acoustic propagational delay of the ear canal contributes the latency of AC-stimulated ABRs. We do not wish to imply, however, that the cross-correlation-determined lags reflect exactly the temporal parameter most relevant to determining ABR latency differences between sites of stimulation nor that propagational delays are the only critical parameter in determining absolute latencies of BC-click-elicited ABRs.

On the other hand, that there are substantive spectral changes between stimulus/measurement sites cannot be denied (see Figs. 2–4). Relative to the vibratory responses recorded near the transducer (the condition of ipsilateral mastoid recording and measurement), the more remotely recorded responses exhibit signs of low-pass filtering. If such filtering occurs at the cochlea, this too would be expected to increase ABR latency. It is not possible from our results to completely separate purely propagational from filtering effects. Both temporal and spectral factors, respectively, have real physical bases here. Again, the temporal delays are asso-
Figure 4 Vibratory responses recorded with the bone vibrator on the mastoid and the accelerometer on the forehead (thin line) versus bone vibrator on the forehead and the accelerometer on the mastoid (heavy line). Amplitude normalized (norm) to maximum peak-to-peak amplitude of ipsilaterally stimulated/recorded response.

Associated (presumably) with modal vibration of the plates of the skull, whereas the spectral changes are most likely associated with coupling of the bone vibrator and/or accelerometer to the skull (i.e., impedance matching between the transducer and the skull). Since the latter also is expected to be influenced by modal vibration, these effects clearly are not independent.

It is worth noting that other researchers (e.g., see Mauldin and Jerger, 1979; Hooks and Weber, 1984; Yang et al, 1987) have observed shorter latencies for BC than AC clicks in premature infants and newborns (with mastoid stimulation). These are quite interesting observations, particularly with regard to the possible roles of modal vibration and impedance of the skull, and suggest that the relationship between the latencies of BC- and AC-click-elicited ABRs, and therefore the effect(s) of vibratory nuances of the skull, varies over ontogeny.

Were there no spectral differences, it intuitively would seem likely that BC stimuli could elicit ABRs of shorter latencies than AC stimuli, by virtue of bypassing the sound propagation delay of the ear canal. However, the results here suggest that vibration of the skull is not free of onset delays under any condition. This is evident in Figure 1 wherein a small, but highly consistent, delay is evident even under the ipsilateral condition. Since under this condition, the stimulus and recording transducers are both on the mastoid, propagation is not expected to be a significant contributor. This, therefore, is a virtual delay resulting from the bandpass characteristics of the combined stimulation and measuring transducers and is seen also in the recorded signal from an artificial mastoid (see Fig. 2). To roughly eliminate this factor, we recorded the output of the accelerometer held tightly on the bone vibrator (directly). Comparing the direct vibrator pickup to real head responses demonstrated typical lags via cross-correlation analysis of about 0.12 msec, which is still small compared with the sound propagation delay of about 0.4 msec attributable to the ear canal. However, the ipsilaterally recorded vibratory response is not likely to precisely reflect the effective onset of vibration at the cochlea (or cochleae) wherein additional propagation delay and/or filtering might be involved. The effective delay might be expected to fall somewhere between lags measured via ipsi- versus contralaterally recorded vibrations. This would lead, at least in some cases, to delays quite similar to the acoustic ear-canal delay. In fact, we have shown elsewhere that, given comparable effective spectra and equal sensation levels, ABRs to BC click stimuli can be demonstrated to have comparable waveform and wave latencies to AC-click-elicited ABRs, even in adults (Durrant and Hyre, in press).

In summary, the results reported here further demonstrate the complexities of skull vibration and possible contributions of the modal vibrations of the plates of the skull to temporal attributes of BC-evoked responses and differences between sites of stimulation. Thus, for example, latency differences of ABR responses obtained with forehead versus mastoid placements are not fully attributed to the well-known difference in efficiency, nor merely to resulting spectral differences. At the same time, individual differences are both substantial and complex and are likely to compromise the reliability of traditional calibration schemes (e.g., mean AC versus BC thresholds or latencies of responses determined in a panel of normal listeners). Hopefully, the more that is learned about the nuances of bone conduction, the more comprehensively the effective stimulus at the level of the cochlea can be specified. At least, the characterization of the effective stimulus should help the clinician to temper interpretation of results obtained using BC stimuli.
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REFERENCES


