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# Effects of Electrode Position on Tone-Burst-Evoked Auditory Brainstem Responses (ABR) in Humans

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**Abstract:** The objective of this study is to investigate the influence of two different positions of the electrodes - forehead/ipsilateral mastoid (Ipsilateral montage) and forehead/nape of the neck (Vertical montage) - on the latency and the amplitude of tone-burst-evoked auditory brainstem responses (ABRs) in normally-hearing adults. This was achieved through the tone-burst stimuli of different carrier frequencies for the purpose of determining the best electrode position. A combination of quasi-experimental and repeated-measure study designs were used throughout the study. Participants were tested with 80, 50 and 30 dBnHL tone-burst stimuli (2-1-2, Blackman window) at the frequencies of 500 Hz, 1000 Hz and 2000 Hz and click stimuli using ipsilateral and vertical montages of the electrodes. Fourteen normal-hearing subjects (Three male and eleven female) aged between 22 and 29 years participated. The results showed that the ABRs wave V latency did not significantly differ for the different montages of the electrodes. This was true for all tone-bursts (500, 1000 and 2000 Hz) except for the 2000 Hz tone-burst at 50 dBnHL. The tone-burst-evoked ABR wave V amplitude was slightly higher in the vertical than the ipsilateral montage for the majority of the stimulus combinations. This study concluded that the tone-burst-evoked ABRs have higher wave V amplitudes when using the vertical electrode montage, (Whether statistically significant or not). The use of the vertical montage of the electrodes is therefore recommended in clinical practice, provided that the visual/subjective analysis technique is used.

**List of Abbreviations:**
ABR: Auditory Brainstem Response
AABR: Automated auditory brainstem response
IIUM: International Islamic University Malaysia
SNR: signal-to-noise ratio
NICU: Neonatal Intensive care unit
dBnHL: decibel normalized-hearing level
dBHL: decibel hearing level
Slow negative 10: $SN_{10}$
$F_{sp}$: F statistics at single point
NOHL: Non-organic hearing loss

**Key words:** Electrode Montage · Tone-burst ABR · Vertical Recording · Ipsilateral Recording

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## INTRODUCTION

Auditory brainstem responses (ABRs) recorded from electrodes placed on the scalp represent the sum of the synchronized neural activity of the ascending auditory pathways between the cochlea and the brainstem. Commonly, ABRs are elicited by transient stimuli such as clicks, tone-bursts and chirps. The tone-burst is a frequency-specific stimulus that is applied for estimating hearing thresholds in difficult-to-test populations, such as infants, children and adults, with a disability or non-organic hearing loss (NOHL) [1-3]. Tone-burst-evoked ABRs are reported to have the potential for determining hearing thresholds with a small estimation error. This is true for normally-hearing and hearing-impaired subjects [4-9].

Despite its advantages, tone-burst-evoked ABR has been reported to have a poor wave morphology and a lesser ABR wave amplitude than the click-evoked ABR [10-12]. This is because the lesser steepness in the onset of the tone-burst stimuli to maintain the frequency specificity and the longer duration of the tone-burst stimuli than the neurons refractory period result in a lesser neural synchrony that leads to smaller responses being recorded and a poor signal-to-noise ratio (SNR) [4]. A poor SNR can only be improved if the number of averagings is increased, which may extend the testing time, or by using an advanced method of signal averaging, such as weighted-averaging, instead of the standard averaging technique.

One of the options for improving the performance of tone-burst ABRs is to find an alternative electrode position for the commonly-used ipsilateral montage, for example, the vertical montage. The effects of the electrode montage on click-evoked ABRs have been extensively studied in the literature [13-22]. Previous findings on the influence of the electrode position on the click-evoked ABR recordings provided information through determining the ABR amplitudes in a visual view or by the direct estimation of the residual noise and evaluation of the SNR [21]. Previous findings in considering the growth of the wave V amplitudes (Based on a visual view) have reported that the wave V amplitude was always higher in the vertical montage [14-17,19-21], with the enhancements in the wave V amplitude being reported in the range of 38 to 110% from the other electrode configurations (For example, the ipsilateral montage) in either adults or infant subjects [14,15,20]. King and Sininger [19] tested 18 adult subjects using click stimuli at 10, 20 and 30 dBSL using vertical, ipsilateral, horizontal and contralateral montages. When using the vertical montage of the electrodes, ABR recordings yielded higher wave V amplitudes, followed by the ipsilateral, contralateral and horizontal electrode montages.

Previously, we conducted a study on 14 normal-hearing adults using ipsilateral and vertical montages and high stimulus repetition rates at multiple stimuli levels in click-evoked ABRs (70, 60, 50, 40, 30 and 20 dBnHL) [14]. Our findings revealed that the vertical montage had a similar wave V latency to the ipsilateral montage and the wave V amplitude was largest when the vertical montage was used (69.2% enhancement, on average) at all intensity levels. More recently, we have conducted another study to investigate the effects of multiple montages in click-evoked ABRs for eleven infant subjects with no-risk factors at lower intensity levels (35 dBnHL) and at two stimulus rates (19.1 and 61.1 Hz) [15]. Similar to the previous report, our results showed that the wave V amplitude was largest when the vertical montage was used, followed by the ipsilateral, contralateral and horizontal montages. This was true for both the low and high stimulus rates.

The previous literature that focused on the direct estimation of the residual noise and SNR evaluation had showed some disadvantages when using the vertical montage. Sininger *et al.* [23] performed their study on 7179 babies (Healthy babies and from the NICU) using automated auditory brainstem response (AABR) screening of the ipsilateral and vertical montages. The stimulus level used in the study was set to 30 dBnHL and 69dB nHL. The screening AABR was stopped, based on the estimation of the residual noise relative to the ABR signal, called the F-test at a single point (Fsp). The recordings were terminated when the algorithm reached a certain pre-set criterion of the SNR (Fsp= 3.1; this indicates a 99% confidence level that the ABR signal was present above the noise). These results revealed that the wave V amplitude was significantly larger when using the vertical instead of the ipsilateral montage of the electrodes. On the other hand, the noise level was higher when using the vertical montage of the electrodes. Thus, the performance was deteriorating due to the smaller SNRs. Consequently, this caused the vertical montage to have a poor Fsp value and less often reached the pre-set criterion than did the ipsilateral montage. The results were further supported by the recent findings of Stevens *et al.*

[21]. Stevens and colleagues conducted research on 30 newborn infants using vertical and ipsilateral montages. Similar to the Sininger *et al.* [23] report, they found higher noise levels when using the vertical/nape electrode montage for the ABR recording, resulting in only a slight improvement when measuring the time efficiency.

Although the direct estimation of the residual noise is important, it may not be feasible for the clinician/audiologist, because not all AEP instruments have the option of directly measuring the residual noise. Without the information of the residual noise, the clinician/audiologist would conclude the ABR testing based on the fixed number of ABR averages (2000 and 4000) or as soon as the ABR peaks were detected. These techniques may have sufficient SNR (Thus minimal residual noise) but not necessarily an ideal SNR, as illustrated by the residual noise estimation [21]. Furthermore, the clinician also has the option of using equipment that comes with other types of algorithms, such as template matching or cross correlation, to detect the presence of the ABR waves [25]. Again, these algorithms would have minimal residual noise (Sufficient SNR) and not an ideal SNR as estimated by a proper noise estimation analysis. Therefore, we can conclude that the advantage of using a vertical montage still holds, should the clinician decide to use visual detection or other types of objective analyses with sufficient SNR, but without directly estimating the residual noise and evaluating the SNR, as described by Stevens *et al.* [21] and Sininger *et al.* [23].

Whilst there are positive reports on the use of the vertical montage to enhance click-evoked ABR wave V amplitudes based on the visual view, there are no reports (To the author's knowledge) investigating the effects of the vertical electrode montage on tone-burst-evoked ABRs amplitude and latency. Therefore, the potential use of the vertical montage to enhance the wave V amplitude in tone-burst-evoked ABR recording requires further investigation. In the present study, click and tone-burst-evoked ABRs with different carrier frequencies (500 Hz, 1000 Hz and 2000 Hz) are compared when using two different electrode montages (Vertical and ipsilateral montages) in normally-hearing subjects.

## MATERIALS AND METHODS

**Participants:** Fourteen adult subjects (Three male and eleven female) aged between 22 and 29 years were involved in this study. All participants had to meet the following criteria, (i) no significant history relating to the presence of a hearing loss, (ii) normal middle-ear functions as shown by a Type A tympanogram, (iii) normal acoustic reflex thresholds at 500, 1000 and 2000 Hz and, (iv) a normal-hearing threshold (Less than 20 dBHL) based on pure-tone audiometry results at octave frequencies between 250 and 8000 Hz.

**Procedure:** This study protocol has received unconditional approval from the International Islamic University Malaysia (IIUM) ethics committee. The ABR recording for each subject was performed in the IIUM Hearing and Speech Clinic electrophysiological room using two-channel GSI Audera equipment (Viasys Healthcare Corporation, Madison, WI, USA with Version 2.6.5.21116 software). We adapted a similar procedure for the ABR recording as described in our previous study and the configuration of the electrode has been described in the early literature [15,26].

Four areas of the subject's skin, at the high forehead, mastoid of the right ear, nape of the neck and shoulder, were cleaned using the Nuprep skin preparation gel to maintain an optimal low impedance (Less than 5kohm). Kendall Meditrace 100 disposable silver/silver chloride electrodes were placed on those cleaned areas and attached with the ABR system snap electrodes. During this test, two electrode montages, ipsilateral and vertical, were used.

In the ipsilateral montage, the active electrode was located at the high forehead, the reference at the mastoid of the right ear and the ground at the shoulder. The test was carried out simultaneously for the ipsilateral and vertical montages using the two channels functions. In the vertical montage, the same active and ground electrodes in the ipsilateral montage were used (And shared between channels) with the reference electrode placed at the nape of the neck. After the electrodes were placed accordingly, the insert phone (GSI TIP-50 insertphone) was placed into the subject's ear canal. Participants were in the supine position and encouraged not to make any movement and highly recommended to sleep during the test.

Alternating tone-burst stimuli were delivered to the subject's right ear via an ear canal insert sound probe. Tone-bursts were gated on and off using a nonlinear Blackman-gating function (2-1-2 cycles). This provided a smooth stimulus onset and offset for yielding frequency specificity [12,27]. Stimulus levels were 80, 50 and 30 dBnHL. Tone-bursts and clicks stimuli were calibrated based on the International Electro-technical Commission (IEC) standard (IEC 60645:32002). The reference levels of 0 dBnHL were psycho-acoustically determined from 25 adults with normal hearing. The reference levels of 0 dBnHL for each of the click and tone-burst frequencies are as follows, 31 dBpeSPL for click stimulus, 23 dBpeSPL for the 2000 Hz tone burst, 20 dBpeSPL for the 1000 Hz tone burst and 24 dBpeSPL for the tone burst 500 Hz. The stimulus rate was set to 39.1 Hz to achieve a sufficiently-high ABR amplitude within an acceptable measuring time as recommended by Gorga *et al.* [28]. A broad-band noise with a level of 40 dBnHL lower than the test ear stimulus level was presented to the contralateral ear. ABRs were also elicited using 0.1 ms alternating polarity click stimuli with the similar stimulus rate, contralateral masker levels and intensity levels as described for the tone-burst stimuli above.

The final ABR responses (For both click and tone-burst) were averaged using 4000 sweeps in a 20 ms time window. The high number of averages was used to yield higher SNRs and consequently, a better identification of the ABR waves. The ABRs were filtered using a 30-3000 Hz band pass filter with a 12-decibel (dB)/octave slope to reduce any electrical activity that was not correlated to the physiological stimulus response. The impedances were maintained at <5kohm and the inter-electrode impedance was balanced and monitored by the GSI Audera impedance check function. The sensitivity of the amplifier was set at ± 50 µV and the noise rejection level at ± 15 µV. The ABR recording was repeated twice for each stimulus and the recording parameters used.

**Data Analysis:** The measures in this study are the wave V amplitude and latency. The ABR wave V latency was determined from the onset of the stimulus to the peak of the ABR wave V in milliseconds (ms). The sound probe's delay time (0.8 ms) was taken into account in the determination of the wave V latency. We measured the wave V amplitude from the wave peak to its following trough ($SN_{10}$) in microvolts (µV). The original and the repeat recordings for all wave V amplitudes and latencies combinations in this study were within the normal test-retest reliability (plus and minus 0.38 ms (2 standard deviation (SD) for absolute latency and 0.14 µV (2 SD)) for the amplitude as described by Dzulkarnain *et. al.* [24]. Therefore, the wave V amplitudes and latencies from the original and repeat waveforms for each matched pair of recordings were averaged to provide a single value.

A paired t-test at the 0.05 significance level was used, because the visual inspection of the data from the histograms and Q-Q plots and the results from the Shapiro Wilk test (p>0.05) revealed the data was normally distributed, which therefore met the parametric assumption. This compared the mean differences of the wave V amplitudes and latencies between these two montages at each recording (Same intensity levels and stimulus type). For pairs of ABRs from the ipsilateral and vertical ABRs that reached significance, the percentage of increment in the wave V amplitude was calculated and averaged across the study's participants. The percentage of increment was calculated using the following formula:

$$\text{Percentage of increment in wave V amplitude} = \frac{\text{wave V amplitude in vertical montage - Wave V amplitude in ipsilateral montage}}{\text{Wave V amplitude in ipsilateral montage}}$$

## RESULTS

Tone-burst and click evoked ABRs were present in all subjects (n=14 for each in the analysis). This was true for all test frequencies and stimulus levels in both electrode montages except for the tone-burst-evoked ABR from 500 Hz and 1000 Hz at 30 dBnHL, where two subjects had an absence of ABRs (n=12). Figure 1 shows the tone-burst and click-evoked ABRs recorded in one subject when using the ipsilateral and vertical electrode montages at all stimulus levels.

Figure 2 shows the mean of the wave V latencies for all types of stimuli at three intensity levels. The paired t-test was not significant for wave V latencies for all the ABRs combinations (p= 0.06-0.84,) except for the ABR recorded from the tone-burst frequency of 2000 Hz at 50 dBnHL (p<0.05). Mean and standard deviations (+/-1 SD) of the wave V amplitude of the subjects' click and tone-burst ABRs, in addition to the results from the paired t-test, are listed in Table 1. As illustrated in Table 1, the mean ABR wave V amplitude was found to be slightly higher for the vertical than the ipsilateral montage except for the 2000 Hz tone-burst at 50 dBnHL. A comparison using paired t-tests showed that the wave V amplitudes obtained using the vertical montage were only significantly larger than the ipsilateral montage for the ABR recorded from the click stimuli at 50 and 30 dBnHL, the 1000 Hz tone-burst at 50 dBnHL and the 2000 Hz tone-burst at 30 dBnHL (p<0.05).

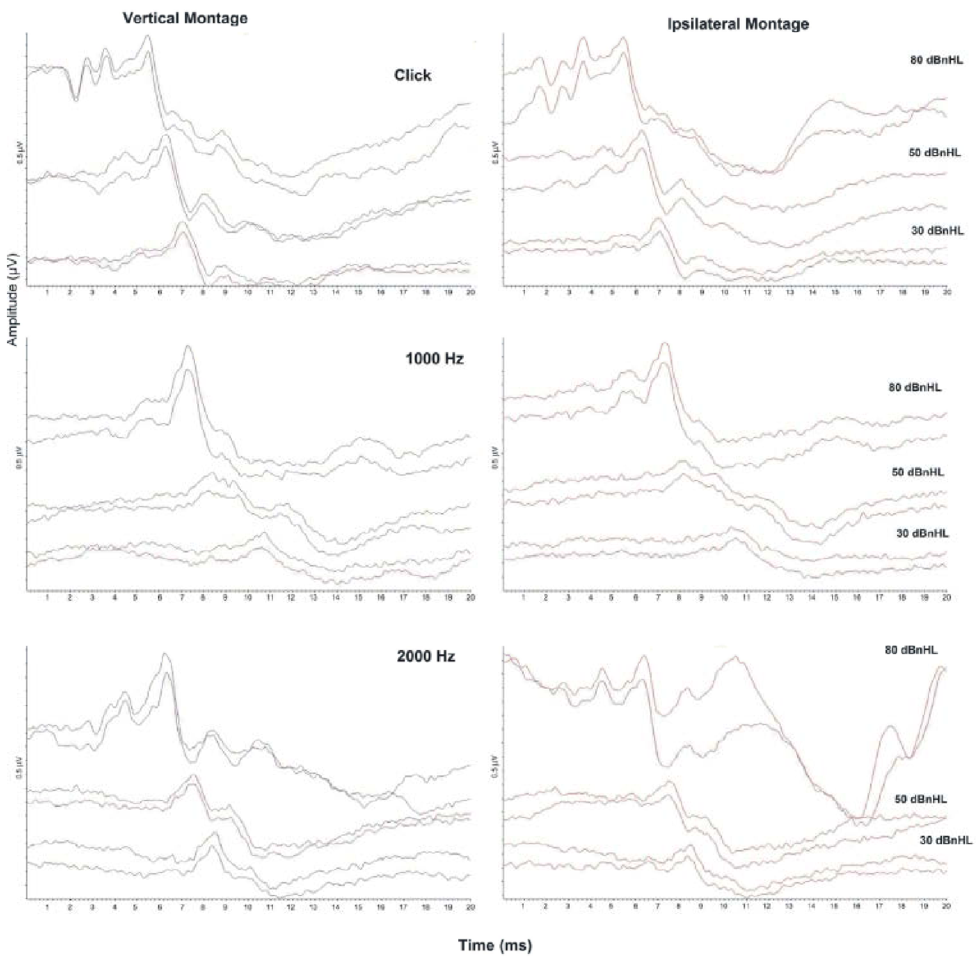


Fig. 1: Two repeats of the ABR waveforms recorded for the vertical montage (Left) and ipsilateral montage (Right) using click (Upper), tone-burst of 1000 Hz (Middle) and 2000 Hz (Bottom Figure)

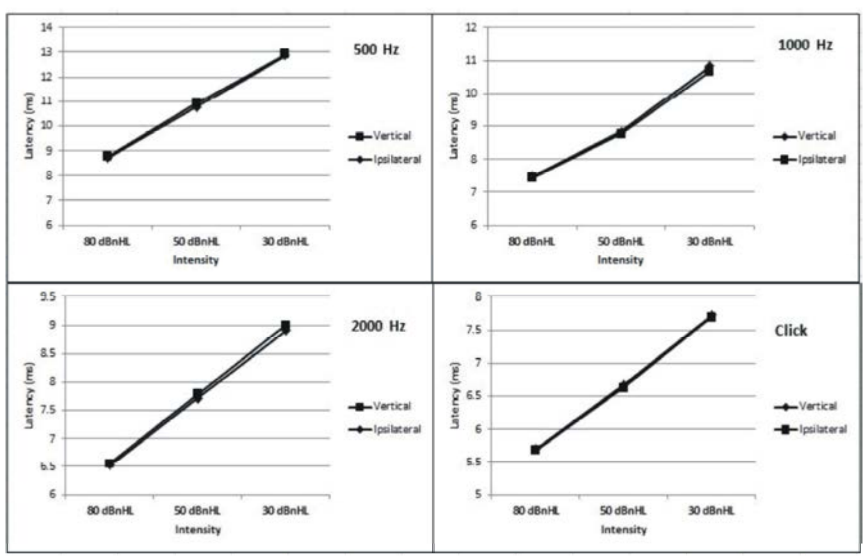


Fig. 2: Mean wave V latency for (i) tone-burst 500 Hz, (ii) tone-burst 1000 Hz, (iii) tone-burst 2000 Hz and, (iv) click for vertical and ipsilateral montages. Note the similarity in both montages wave V latencies in all types of stimuli.

Table 1: Mean and SD for ABR wave V amplitude from ipsilateral and vertical montages at different intensity levels. The p-values of the paired t-test analysis are shown in the last column

| Stimulus Types | Montages | Mean (SD) | t (df) | p-value |
|---|---|---|---|---|
| 80 dBnHL | | | | |
| 500 | Vertical | 0.32 (0.13) | 0.95(13) | 0.36 |
| | Ipsilateral | 0.31 (0.11) | | |
| 1000 | Vertical | 0.50 (011) | 1.21 (13) | 0.25 |
| | Ipsilateral | 0.47(0.10) | | |
| 2000 | Vertical | 0.47 (0.13) | 2.12(13) | 0.06 |
| | Ipsilateral | 0.42 (0.11) | | |
| Click | Vertical | 0.57 (0.10) | 1.66 (13) | 0.12 |
| | Ipsilateral | 0.54 (0.12) | | |
| 50 dBnHL | | | | |
| 500 | Vertical | 0.11(0.07) | 2.02 (13) | 0.07 |
| | Ipsilateral | 0.08 (0.05) | | |
| 1000 | Vertical | 0.09 (0.04) | 3.16 (13) | 0.008 |
| | Ipsilateral | 0.06 (0.02) | | |
| 2000 | Vertical | 0.12 (0.08) | -1.60 (13) | 0.13 |
| | Ipsilateral | 0.13 (0.08) | | |
| Click | Vertical | 0.34 (0.14) | 2.45 (13) | 0.03 |
| | Ipsilateral | 0.30 (0.13) | | |
| 30 dBnHL | | | | |
| 500 | Vertical | 0.04 (0.03) | 1.40 (11) | 0.19 |
| | Ipsilateral | 0.03 (0.01) | | |
| 1000 | Vertical | 0.04 (0.03) | 2.17 (11) | 0.06 |
| | Ipsilateral | 0.03 (0.01) | | |
| 2000 | Vertical | 0.08 (0.05) | 2.41 (13) | 0.03 |
| | Ipsilateral | 0.06 (0.05) | | |
| Click | Vertical | 015 (0.14) | 2.48 (13) | 0.03 |
| | Ipsilateral | 0.10 (0.10) | | |

The percentages of increments in the wave V amplitude for the vertical montage in reference to the ipsilateral montage for these stimuli and recording combinations were 17.95% (SD= 29.48%) for the click-evoked ABR at 50 dBnHL, 52.36% (SD=88.31) for the click-evoked ABR at 30 dBnHL, 52.52% (SD: 59.37%) for the 1000 Hz tone-evoked ABR at 50 dBnHL and 68.87% (SD= 144.25) for the 2000 Hz tone-evoked ABR at 30 dBnHL.

## DISCUSSION

The obtained findings revealed that there was no significant change in the tone-burst-evoked ABR wave V latency for both electrode montages. This was true for all tone-bursts, except for the 2000 Hz tone burst at 50 dBnHL. Thus, the overall findings are in agreement with the studies on click-evoked ABRs on both adult and infant subjects [13-15]. Our data have shown that the wave Vs of tone-burst-evoked ABRs have slightly higher amplitudes when using a vertical electrode montage than the ipsilateral montage for all stimulus types and intensity levels. This is despite not all pairs of vertical ABRs versus ipsilateral ABR wave V amplitudes reached significance. These trends are consistent with the ABR evoked by the click stimuli on the same study participants across the different intensity levels.

The present finding suggested the tone-burst-evoked ABRs behave similarly to the click-evoked ABRs that had previously been reported as producing a higher wave V amplitude from the vertical montage, while having no effects on the wave V latency [13-16,19,20,22]. The tone-burst-evoked ABR wave V amplitudes recorded using the vertical montages in this study were from 55.52% to 68.87% larger than the ipsilateral montage. This is consistent with the previous literature that showed the vertical montage could produce 38 to 110% larger wave V amplitudes than the ipsilateral montage in adult or infant subjects when using a click stimulus [14,15,20]. The increase in the wave V amplitude in the tone-burst-evoked ABR recorded from the vertical montage is also comparable with the 17.95 to 52.36% increase in the wave V amplitude from the vertical click-evoked ABR obtained from the same study's subjects.

The limitations in this study are acknowledged. We did not account for gender when analysing the data, with the majority of our subjects being female. Gender was also reported as one of the factors that should be considered when testing the ABR, because females have shorter latencies than the males with a comparable head size [29,30]. The present study was also not performed using a full experimental design; for example, no randomization was made, in spite of our attempt to improve the internal validity through the use of a repeated measure study design (For example, exposing all study participants' to all types of stimuli). All these limitations could partially influence our findings; consequently, our results cannot be generalized beyond the subject, the stimulus and the recording parameters used.

## CONCLUSION

The ABR wave V amplitude is slightly higher when using a vertical than the ipsilateral montage across the different stimulus types used in the present study. This was true for all tone-bursts, except for the 2000 Hz tone burst at 50 dBnHL. In general, the tone-burst-evoked ABR wave V latency does not change with the electrode position. Both findings are generally consistent with the click-evoked ABR recorded in the same study participants. Thus, the vertical montage could be considered for tone-evoked ABR recordings as an alternative to the ipsilateral montage in clinical practice. The present study used only a visual view for the criterion to detect the presence of ABR waveforms. As described earlier in this paper, this technique may have sufficient SNR, but not an ideal SNR. This study therefore supports further investigations to evaluate the performance of tone-burst-evoked ABRs using a vertical montage based on the estimation of the residual noise and SNRs near the hearing threshold in both normally-hearing subjects and in patients with a hearing loss.

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