

Towards optimal selection of stimuli polarity method for effective evoking auditory brainstem responses

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Towards eliminating stimulus artifacts, alternating polarity stimuli have been widely adopted in eliciting the auditory brainstem response. However, considering the difference in the physiologic basis of the positive and negative polarity stimuli on the auditory system, it is unclear whether alternating polarity stimuli would adversely affect the auditory brainstem response characteristics. This research proposes a new polarity method for stimulus artifacts elimination, Sum polarity, that separately utilized the rarefaction and condensation stimuli and then summed the two evoked responses. We compared the waveform morphology and latencies of the auditory brainstem responses evoked by familiar stimuli (including click, tone-burst, and chirp) with different polarity methods in normal-hearing subjects to investigate the new method's effectiveness. The experimental results showed that alternating polarity of the click and chirp had little effect on the auditory brainstem response. In contrast, alternating polarity affected the waveform morphology and latencies of the auditory brainstem responses to the low-frequency tone-burst, with the effect decreasing as the stimulus frequency increased. These results demonstrated the performance of any polarity method is related to the characteristics of the stimulus signal itself, and no polarity method is optimal for all types of stimuli. Based on the analysis of experimental results, a fixed polarity and alternating polarity were recommended for the click and chirp auditory brainstem responses, respectively. Furthermore, considering the apparent latency differences between the responses to opposite polarity stimuli, the Sum polarity was suggested for the tone-burst auditory brainstem responses. Moreover, this work verified the feasibility of the Sum polarity, which offers another choice for eliminating stimulus artifacts in an evoked potential acquisition.

Keywords

Auditory brainstem response; Alternating polarity; Rarefaction; Condensation; Hearing

1. Introduction

The auditory brainstem response (ABR) is a response evoked by an acoustic stimulus, in which the waveform characteristics are directly related to the parameters of the acoustic stimulus, such as stimulus type, stimulus intensity, stimu-

lus rate, and stimulus polarity (or phase) [1]. At present, the commonly used stimulus types in clinical diagnosis are click (as a gold standard) [2] and tone-burst (for newborn hearing screening) [3, 4], while the chirp is gradually emerging as a potential stimulus method [5]. The stimulus polarity refers to the initial phase of the stimulus, which is characterized by either a positive-going zero crossing (0 degree) or a negative-going zero crossing (180 degrees) [6].

From the physiological perspective, different polarity (positive or negative) stimuli have different mechanisms of action on the auditory system [7, 8]. The rarefaction stimulus (negative polarity) generates an outward movement of the tympanic membrane and stapes footplate, then mobilizes the basilar membrane upward toward the scala vestibule, thus depolarizing the hair cells, which leads to neural firing. On the other hand, the condensation stimulus (positive polarity) effects at the cochlea are opposite to those of the rarefaction. The condensation stimulus produces an inward movement of the tympanic membrane. It then mobilizes the basilar membrane in a downward direction toward the scala tympani, which causes the hyperpolarization of the hair cells [9, 10]. Previous studies found that the auditory neurons display phase-locking characteristics in the response, especially for low-frequency stimuli [11].

Several studies have been done regarding the effect of stimulus polarity on the ABR signal since the early 1990s [6, 12–15]. These studies mainly focused on comparing ABRs to the rarefaction and condensation clicks with conclusions that were quite controversial. For instance, in persons with normal hearing, some studies reported no significant differences between the ABRs induced by two opposite polarity clicks when averaged across subjects [6], while others found that the majority of subjects had shorter latencies with rarefaction clicks and the minority had shorter latencies with condensation clicks [14]. Many studies argued that the rarefaction click had higher diagnostic sensitivity. Hence it is used more often in clinical applications [16]. Afterward,

some investigators took into account alternating polarity in the research on the effect of stimulus polarity or phase on the ABR since it could serve as a means of eliminating stimulus artifacts [17, 18]. In addition, there were a few studies about the effect of tone-burst polarity on the ABR [6, 12, 14]. For instance, Fowler investigated the effects of the stimulus phase on the ABR elicited by the rarefaction and condensation tone pips with 1 ms rise-fall times and no plateau [12], and Orlando and Folsom examined the responses to single-cycle sinusoids with the rarefaction and condensation polarities [14]. They concluded that stimulus polarity affected the ABR latencies for low-frequency stimuli more obviously.

It is widely recognized that the ABR signal appears within 10 ms after an acoustic stimulus, with an amplitude of 0.1–1 μ V [1]. The duration of a standard click is usually only 100 μ s, so the stimulus artifact does not contaminate the ABR components (waves I–V) regardless of the rarefaction or condensation polarity [19]. For tone-burst stimuli, if the duration is too short, it leads to spectral splatter, but if the duration is too long, it is not conducive to elicit a well-defined ABR waveform. Hence, the tone-burst with a “2-1-2” cycle envelope is considered a reasonable compromise and often used in the current studies, consisting of 2 cycles rise/fall time and 1 cycle plateau [20]. However, it means that the duration of such a tone-burst may be quite long. For example, the duration of a 1000 Hz tone-burst is 5 ms. This, coupled with the faint amplitude of the ABR signal, there is no doubt that if a single-polarity is used rather than alternating polarity, the stimulus artifacts will submerge the ABR signal, especially for the low-frequency tone-burst. Various chirp stimuli are designed based on the traveling wave delay characteristics of the human cochlear basilar membrane, so their duration is usually more than 10 ms [21, 22]. For the same reason, alternating polarity should also be used for chirp ABRs to avoid stimulus artifacts masking the target signal. It is worth noting that alternating polarity is the most frequently used polarity method in devices [17].

Given the difference in the physiological effects of rarefaction and condensation stimuli on the auditory system, whether alternating polarity adversely affects the ABR signal has not been determined. Furthermore, previous studies showed that the ABRs induced by opposite polarity stimuli might differ in latency (especially for low frequencies), which may obscure the response waveform [14, 23]. Therefore, Gorga *et al.* [6] thought that a more conservative approach might record the ABRs elicited by opposite polarity stimuli separately and then combine them. Still, no attempt has been made to implement this concept to be best of our knowledge so far.

2. Methods

2.1 Subjects

We recruited seven normal-hearing subjects (three males and four females), aged between 22 and 30, with an average age of 26 years. For each subject, both ears were tested, and

the pure-tone audiometric thresholds were equal to or better than 15 dB HL for frequencies from 250 to 8000 Hz. Before the experiments, the subjects have been explained the purpose and the details of the experiment, then all subjects read and signed an informed consent form. The research was carried out in accordance with approvals by the Institutional Review Board (IRB) of the Shenzhen Institutes of Advanced Technology, Chinese Academy of Sciences.

2.2 Stimuli

The stimulation scheme used took a click as an example, as shown in Fig. 1. The first three polarity methods are the existing conventional methods, which are condensation (①), rarefaction (②), and alternating polarity (③). For each polarity method, the ABR is obtained by averaging responses to 3000 sweeps. The fourth polarity method is a new one, named Sum polarity (④), in which the condensation and rarefaction stimuli are presented 1500 times separately. Then two ABR signals with stimulus artifact of opposite polarity are obtained from 1500 averages, and finally, they are added and divided by 2.

Three types of stimuli were used in the experiment, including the common click and tone-burst, as well as the emerging chirp. The click is produced by applying 100 μ s of electric pulses to the earphones, limited to 200–10000 Hz. Five frequencies of tone-bursts are used, including low-frequency (500 and 1000 Hz) and high-frequency (2000, 4000, and 8000 Hz), which are windowed using a Blackman-gated function and have a “2-1-2” cycle envelope. As shown in Fig. 2, the total duration of tone-burst is 10 ms at 500 Hz, 5 ms at 1000 Hz, 2.5 ms at 2000 Hz, 1.25 ms at 4000 Hz, and 0.625 ms at 8000 Hz, and their peak energies are at 500, 1000, 2000, 4000, and 8000 Hz, respectively. In addition, a representative chirp is employed with a duration of more than 10 ms and a frequency range of 200–10000 Hz, and its temporal waveform, as well as amplitude spectrum, can be seen in Elberling *et al.* (Fig. 8) [22]. The stimuli were presented at a level of 70 dB nHL and a rate of 25/s and delivered through the Etymotic Research ER-2 insert earphone. No masking noise was provided to the contralateral ear during the experiment.

2.3 Procedures

The ABRs were recorded with a custom board controlled by a laptop’s MATLAB program. The circuit board could realize stimulus presentation and physiological signal recording, and its main chip was ADS1299 (low-noise, 16 kSPS, 24-bit) [24]. The subjects were placed on a couch in a sound-treated and electrically shielded room. The ABR signals were picked up differentially between two electrodes: one placed as high as possible on the midfrontal area (Fz) and the other placed on the ipsilateral mastoid (M1 or M2). An additional electrode at the contralateral mastoid served as ground. The impedance between the skin and the electrodes was maintained below 5 k Ω .

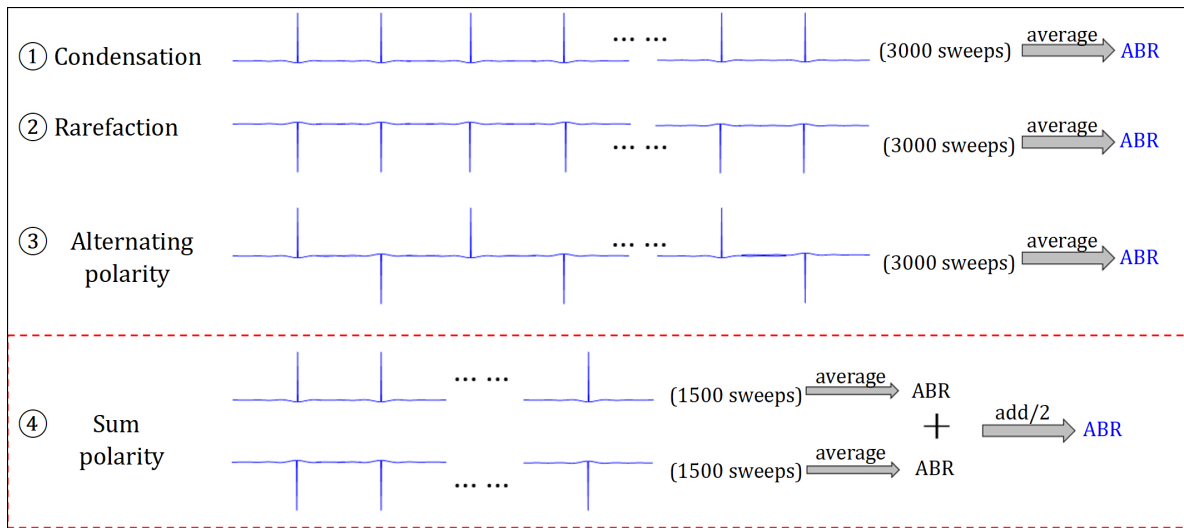


Fig. 1. Schematic diagram of the experimental stimulation approaches (take clicks as an example). ①Condensation; ②Rarefaction; ③Alternating polarity; ④Sum polarity.

The ABR experiment was mainly divided into three sessions, as described below. First, the clicks with condensation (①), rarefaction (②), and alternating polarity (③) were provided, respectively, and each trial was terminated after 3000 sweeps. Then, the tone-bursts with frequencies of 500, 1000, 2000, 4000, and 8000 Hz were presented in turn. For each frequency of tone-burst, two opposite phases of tone-burst stimuli were played 1500 times respectively (for ④), followed by the tone-burst with alternating polarity 3000 times (③). Finally, the subjects were provided with the chirp, which was played in the same way as the tone-burst. To test the response repeatability, each trial under the same stimulus conditions was repeated twice. Only when the response obtained was repeatable, the data of the subject was available for analysis. During the experiments, the subjects were instructed to be as quiet as possible and rest for five minutes every half hour to prevent fatigue.

2.4 Data analysis

The MATLAB software was used to analyze the ABR recordings collected. First, the raw data were band-pass filtered from 100 to 3000 Hz using filter slopes of 12 dB/octave and segmented according to the acoustic stimuli. Then, for the condensation and rarefaction clicks and all the stimuli with alternating polarity, the ABR signals were obtained by averaging 3000 epochs. Afterward, two recordings with opposite phases were averaged for each stimulus after 1500 sweeps separately and then added to obtain the target signal described by the Sum polarity method in Fig. 1.

For statistical analysis, the mean and standard deviation of the latencies for waves I, III, and V of the ABRs evoked by all stimuli were calculated across all subjects ($N = 14$ ears), respectively. The data under each stimulus condition were checked for normality by the Shapiro-Wilk test to ensure that none of the datasets deviated significantly from a normal dis-

tribution. Then, to compare the latencies for waves I, III, and V of the click ABR among four polarity methods (condensation, rarefaction, alternating polarity, and Sum polarity), we carried out the homogeneity of variance test. We then did the analysis of variance (ANOVA) to check whether the latency differences among different polarity methods were statistically significant. Similarly, the paired t -test was performed to analyze the latency difference of the tone-burst and chirp ABRs between alternating polarity and Sum polarity methods. Note that the significance level was set at 0.05 for all analyses.

3. Results

3.1 ABRs to click with condensation, rarefaction, alternating polarity, and Sum polarity methods

The ABR waveforms evoked by click with condensation (①), rarefaction (②), alternating polarity (③), and Sum polarity (④) methods from one subject are shown in Fig. 3, corresponding to the four stimulation approaches in Fig. 1. In the first two panels, the spike at abscissa 0 represents the click stimulus artifact. In contrast, the alternating polarity and Sum polarity methods eliminate stimulus artifacts of click, as shown in the last two panels. For the waveform morphology of click ABRs, the responses to four polarity methods have similar waveform differentiation, in which waves I–V are visible. Note that the subject's waves IV and V appear as a single complex wave.

Table 1 gives the mean latencies with standard deviations and significance level for waves I, III, and V of the click ABRs from four stimulus polarity methods. The ANOVA showed the latency differences for waves I, III, and V among four polarity methods were not significant ($P > 0.05$ for all waves), which means that the polarity method has no significant effect on the latencies of the click ABR.

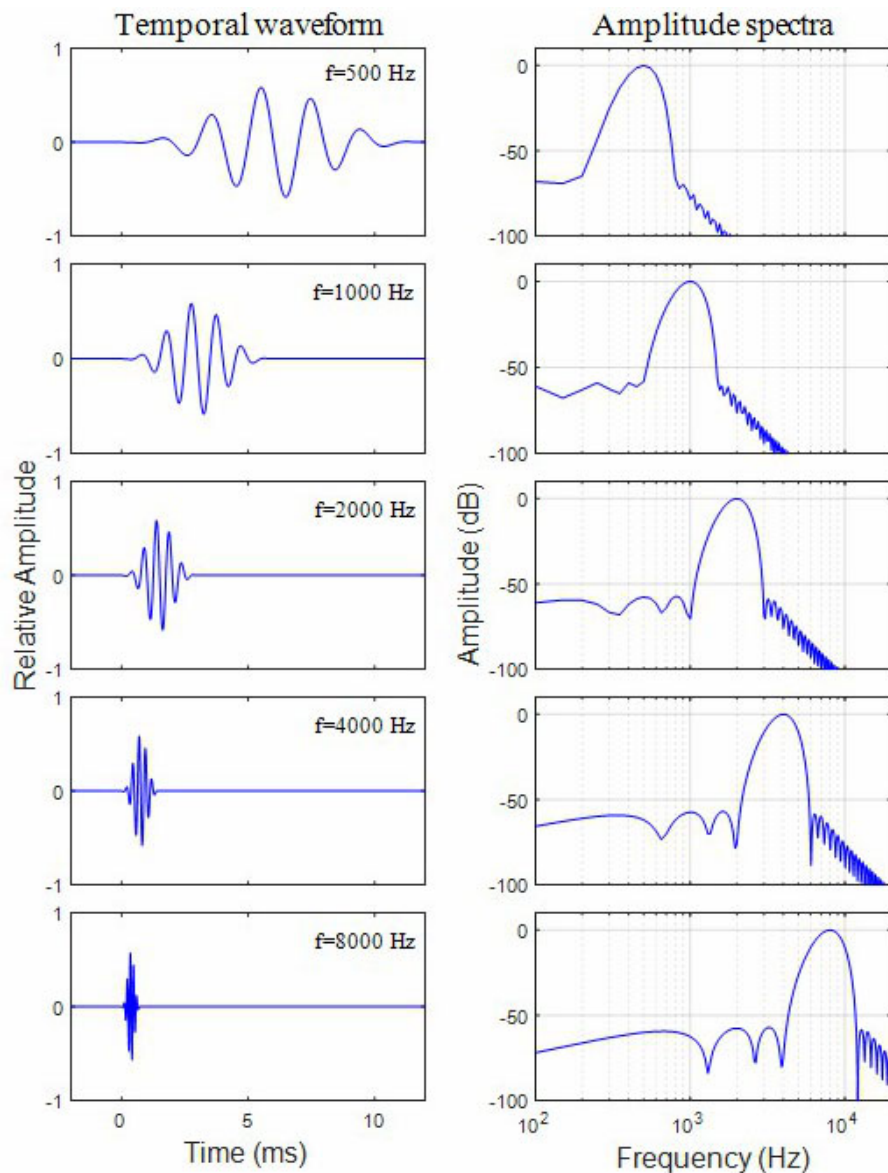


Fig. 2. The tone-burst stimuli' temporal waveform and amplitude spectra (of frequencies 500, 1000, 2000, 4000, and 8000 Hz).

3.2 ABRs to five frequency tone-bursts with alternating polarity and Sum polarity methods

Fig. 4a shows the ABRs evoked by low-frequency tone-burst stimuli with alternating polarity (③) and Sum polarity (④) methods from one subject. For 500 and 1000 Hz tone-burst ABRs, well-formed waves III and V are observed for the Sum polarity method, while the waveform morphology of alternating polarity responses is poor. Besides, wave I of the 500 Hz tone-burst ABRs with both polarity methods was absent.

Fig. 4b illustrates the corresponding ABRs elicited by high-frequency tone-bursts, in which the frequencies of tone-burst stimuli include 2000, 4000, and 8000 Hz. As the stimulus frequency increases, the waveform morphology of tone-burst ABRs becomes better, and the advantage of ABR waveforms for the Sum polarity over that of alternating po-

larity decreases. Specifically, the 2000 Hz tone-burst ABRs for the alternating polarity and Sum polarity methods have apparent waves I, III, and V, but wave II of the latter is more apparent than that of the former (which is barely detectable). When the frequency increases to 4000 Hz, the ABR signals of the two methods have similar features. In a word, alternating polarity affects the waveform morphology of tone-burst ABR for low-frequencies, and the effects decrease as the stimulus frequency increases.

The mean latencies with standard deviations and significance level for waves I, III, and V of the tone-burst ABRs from alternating polarity and Sum polarity methods are listed in Table 2. The latencies for the ABR waves I, III, and V decrease as the tone-burst frequency increases, which is generally accepted. For 1000 Hz tone-burst ABRs (low-frequency), the mean latency of wave I from Sum polarity (1.88 ms) is

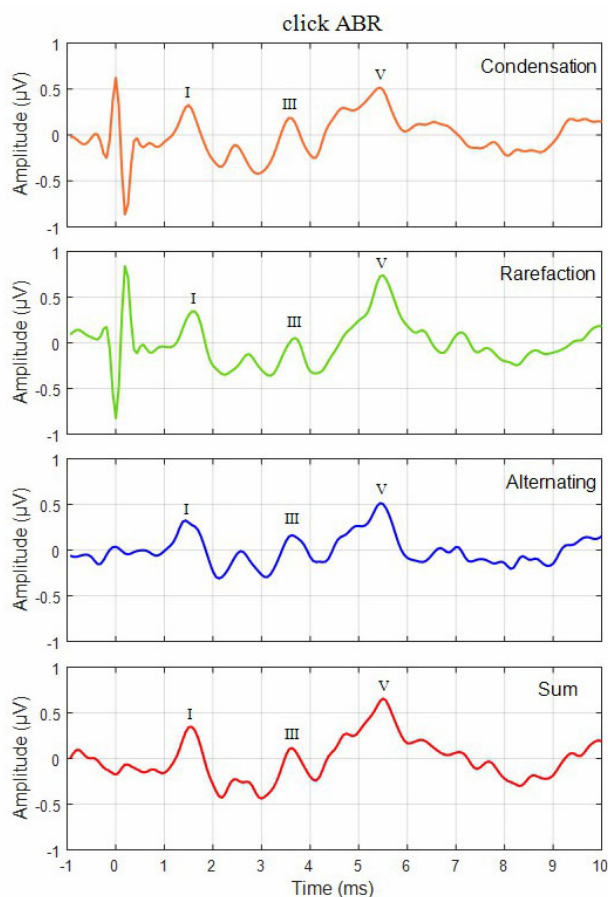


Fig. 3. The click ABRs to condensation (orange curve), rarefaction (green curve), alternating polarity (blue curve), and Sum polarity (red curve) methods for a representative subject.

Table 1. The mean latencies (ms) with standard deviations and significance level for the click ABR waves I, III, and V.

	Wave I	Wave III	Wave V
	Mean \pm SD	Mean \pm SD	Mean \pm SD
Condensation	1.50 \pm 0.12	3.56 \pm 0.14	5.44 \pm 0.21
Rarefaction	1.56 \pm 0.14	3.62 \pm 0.12	5.50 \pm 0.20
Alternating	1.50 \pm 0.14	3.60 \pm 0.15	5.44 \pm 0.23
Sum	1.52 \pm 0.13	3.60 \pm 0.16	5.48 \pm 0.24
F	0.698	0.331	0.260
P-value	0.503	0.72	0.772

Note: SD denotes standard deviation.

shorter than that of Alternating polarity (2.12 ms), and this difference is significant ($P < 0.001$, paired t -test). For 500 Hz and 1000 Hz tone-burst ABRs (low-frequency), the mean latency of wave V for the two polarity methods are 5.88 ms and 5.81 ms, respectively, and there is no significant difference between the two polarity methods ($P > 0.05$, paired t -test). The latency differences between the two methods decrease with the increase of stimulus frequency. The mean latency differences of all the waves are not apparent for high-frequency tone-burst ABRs (all less than 0.1 ms).

3.3 ABRs to chirp with alternating polarity and Sum polarity methods

The chirp ABRs with alternating polarity (③) and Sum polarity (④) methods from one subject are shown in Fig. 5. Similar to the click ABRs, the alternating polarity chirp ABR exhibits almost the same differentiation characteristics as the ABR signal with Sum polarity, both of which have clear waves I–V and high amplitude.

Table 3 presents the mean latencies with standard deviations and significance level for waves I, III, and V of the chirp ABRs with alternating polarity and Sum polarity. There is no significant difference in the latencies of all the waves of the chirp ABRs between the two polarity methods ($P > 0.05$, paired t -test).

4. Discussion

There has been a debate regarding the effects of stimulus polarity on the ABR signal. No consensus on which stimulus polarity method (rarefaction, condensation, or alternating polarity) could provide more accurate diagnostic information. However, alternating polarity is currently the only way to eliminate stimulus artifacts in clinical applications. To test whether alternating polarity could adversely affect the waveform characteristics of the ABR while eliminating stimulus artifacts, another method that could eliminate stimulus artifacts was implemented. Although the idea of the Sum polarity method has been vaguely mentioned in previous literature [6], it was first conceptualized and implemented. Besides, it is worth noting that, unlike most studies, we emphasized the analysis of waveform morphology. Since waveform morphology is a subjective parameter that is difficult to quantify, most studies focused more on latency or amplitude. Yet, clinicians usually make a preliminary diagnosis based on the ABR waveform morphology and discuss it in their diagnosis interpretation, which is why we paid attention to the waveform morphology [25].

4.1 Analysis of the polarity effect for click ABR

The results indicated that the rarefaction and condensation click ABRs are similar in waveform differentiation and latency, which agrees with previous studies [6, 14]. And the response to alternating polarity click is similar to those of the rarefaction and condensation. As a result, it is not surprising that the waveform of the response to Sum polarity is not significantly different from that of alternating polarity. Given that the phase-locking ability was a predominantly low-frequency phenomenon reported in the literature [11, 23], and the click ABR is dominated by high-frequency neural responses [26], the above conclusions were expected. Though little effect of click polarity on the ABR was found from the average data, the responses to opposite polarity click may vary slightly from subject to subject according to the literature [13]. Thus, for subjects with normal hearing, a conservative method is to use a fixed click polarity. After all, the click artifact would not hinder ABR component identification.

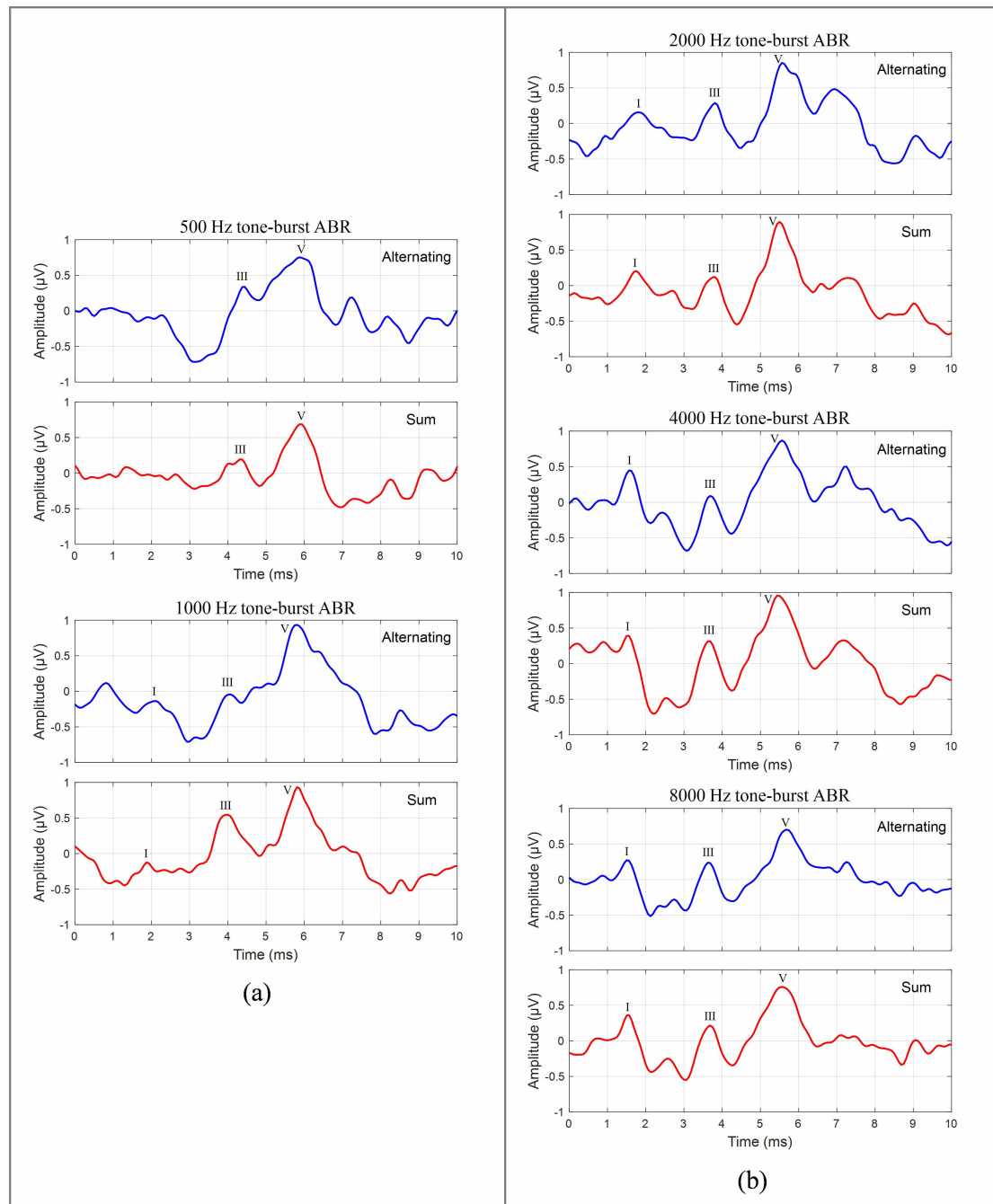


Fig. 4. The tone-burst ABRs to alternating polarity (blue curve) and Sum polarity (red curve) methods for a representative subject. (a) Low-frequency tone-burst evoked ABRs (500 and 1000 Hz). (b) High-frequency tone-burst evoked ABRs (2000, 4000, and 8000 Hz).

4.2 Analysis of the polarity effect for tone-burst ABRs

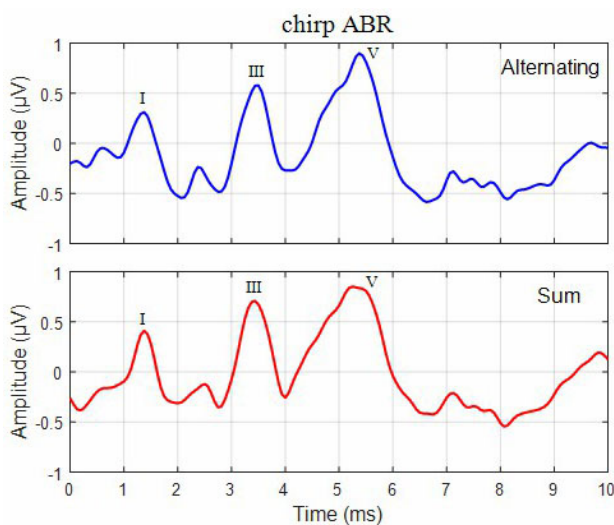
Regarding the effect of tone-burst polarity on the ABR, some researchers have investigated single-cycle sinusoids, 1 ms rise/fall time tone pips with no plateau, etc. [6, 12, 14]. Still, no research has been conducted on “2-1-2” cycle tone-bursts that is a compromise between the desired frequency specificity and the required temporal brevity. The experimental results revealed that alternating polarity affected the characteristics of the low-frequency tone-burst ABRs, including waveform morphology and latency, and the effects

decreased as the stimulus frequency increased, which is consistent with previous studies [12, 14]. Moreover, the 2000 Hz tone-burst ABR with alternating polarity was close to that of the Sum polarity, which verified that the known phase-locking ability of the auditory system might gradually be lost when the frequency exceeds 2000 Hz [6, 11, 27]. For low-frequency tone-bursts, it is well known that the ABR signal is more difficult to obtain [28, 29], so it is not surprising that wave I of the 500 Hz tone-burst ABRs with both methods was absent in Fig. 4a. Gorga *et al.* [30] reported that it was

Table 2. The mean latencies (ms) with standard deviations and significance level for the tone-burst ABR waves I, III, and V.

Frequency		Wave I		Wave III		Wave V	
		Mean \pm SD	<i>P</i> -value	Mean \pm SD	<i>P</i> -value	Mean \pm SD	<i>P</i> -value
500 Hz	Alternating	–	–	4.43 \pm 0.17	0.081	5.88 \pm 0.25	1.000
	Sum	–	–	4.31 \pm 0.18		5.88 \pm 0.22	
1000 Hz	Alternating	2.12 \pm 0.17	<0.001	4.06 \pm 0.20	0.423	5.81 \pm 0.20	1.000
	Sum	1.88 \pm 0.15		4.00 \pm 0.19		5.81 \pm 0.21	
2000 Hz	Alternating	1.81 \pm 0.16	0.345	3.81 \pm 0.17	1.000	5.56 \pm 0.23	0.505
	Sum	1.75 \pm 0.17		3.81 \pm 0.17		5.50 \pm 0.24	
4000 Hz	Alternating	1.56 \pm 0.16	1.000	3.68 \pm 0.22	1.000	5.50 \pm 0.27	0.547
	Sum	1.56 \pm 0.15		3.68 \pm 0.23		5.44 \pm 0.25	
8000 Hz	Alternating	1.50 \pm 0.18	1.000	3.62 \pm 0.21	1.000	5.50 \pm 0.29	1.000
	Sum	1.50 \pm 0.19		3.62 \pm 0.24		5.50 \pm 0.29	

Note: SD denotes standard deviation—denotes missing data due to the absence of wave I in some subjects.

**Fig. 5. The chirp ABRs to alternating polarity (blue curve) and Sum polarity (red curve) methods for a representative subject.**

less successful evoking the ABR for alternating polarity tone-burst with a frequency below 1000 Hz. According to Table 2, our data suggested that for low-frequency tone-burst ABRs, the mean latency of wave I from Sum polarity is shorter than that of alternating polarity ($P < 0.05$, paired *t*-test).

In contrast, the mean latency of wave V for the two methods is not significantly different ($P > 0.05$, paired *t*-test). Therefore, it implied that the latency of wave I of the low-frequency tone-burst responses was sensitive to stimulus polarity. In contrast, the latency of wave V is hardly affected by stimulus polarity. Previous findings supported this finding that alternating polarity had a more significant effect on the early components of the ABR than on wave V, which is almost unaffected by polarity [14, 31]. Considering the above conclusions, the Sum polarity is recommended for evoking tone-burst ABR.

4.3 Analysis of the polarity effect for chirp ABR

The chirp ABR was studied intensively after 2000 [21, 22, 32], among which the research of Elberling *et al.* [22] was

Table 3. The mean latencies (ms) with standard deviations and significance level for the chirp ABR waves I, III, and V.

	Wave I		Wave III		Wave V	
	Mean \pm SD	<i>P</i> -value	Mean \pm SD	<i>P</i> -value	Mean \pm SD	<i>P</i> -value
Alternating	1.38 \pm 0.13	1.000	3.48 \pm 0.14	0.456	5.30 \pm 0.22	0.544
Sum	1.38 \pm 0.12		3.44 \pm 0.14		5.25 \pm 0.21	

Note: SD denotes standard deviation.

a representative. Although the chirp is not a new stimulus type, no one has studied the effect of chirp polarity on the ABR. The present results illustrated that the chirp ABR with alternating polarity and Sum polarity have similar waveform morphology and latencies. For one thing, it is known that the click ABR is dominated by high-frequency energy, and the chirp is designed to compensate for the cochlear traveling wave delay, so the entire frequency components of the chirp theoretically contribute effectively to the ABR [21]. However, our results implied that the low-frequency dominant phase-locking effect might be covered by the high-frequency neural dominance in normal-hearing subjects, which might be due to the greater density of nerve fibers at the base of the cochlea compared with more apical regions [30]. The chirp has the same broadband spectrum as the click in terms of the spectrum [33]. Hence, like the click polarity, the chirp polarity has little or no effect on the ABR, which is reasonable. Given this and the fact that the chirp is a relatively effective stimulus (compared with traditional stimuli) [34], alternating polarity chirp is sufficient for eliciting the response in practice. The advantage of alternating polarity is that the processed ABR signal can be observed in real-time while the trial is in process. The trial could be terminated after any sweeps as long as the target waveform becomes clear (or the required signal-to-noise ratio is reached).

In contrast, the Sum polarity is implemented offline, increasing the complexity of operation to a certain extent, which is a limitation of the new method. However, suppose the background noise condition of a device in a particular working environment is known. In that case, we could pro-

gram the Sum polarity method in the device's software system instead of offline processing, thereby improving work efficiency. Specifically, suppose we know how many sweeps it takes to obtain a clear ABR signal when using a specific device in a particular working environment, e.g., 2000 sweeps. In that case, we could set the condensation tone-burst for the first 1000 sweeps and the rarefaction tone-burst for the subsequent 1000 sweeps in the device's system, then use the Sum polarity described in the Method section.

4.4 Analysis of the effect of polarity mechanism

As stated above, the physiologic basis for rarefaction and condensation stimuli at the cochlea differ. Nevertheless, no previous work has provided a theoretical reason for the difference of the neural response depending on stimulus polarity when the neural response is triggered. At the initiation of the neural response, the effect of stimulus polarity at the cochlea is translated into timing differences [23]. When the stimulus reaches the cochlear basilar membrane, the low-frequency components travel to the apex of the cochlea at a relatively slow speed for a relatively long distance. In contrast, the high-frequency components travel a relatively short distance to the base of the cochlea with a relatively fast velocity [35]. As a result, the period of the traveling wave for low frequencies is relatively more extended than high frequencies, which is believed to be why significant latency differences between rarefaction and condensation stimuli occur for low-frequency stimuli. As the neural firings from the cochlea ascend along the brainstem pathway, numerous factors may contribute to the final waveform, of which the mechanism is not yet precise. Based on the latency differences between opposite polarity stimuli, when the raw data is segmented and averaged, the responses to alternating polarity stimuli may introduce latency "jitter", which would obscure the response and result in a poor waveform. In such cases, the Sum polarity (versus alternating polarity) was recommended, which increases the likelihood of inducing clear ABR waves by summing two opposite polarity responses stably formed on the scalp surface.

Although the alternating polarity effect is dominated by low-frequency, the low-frequency effect may be covered when high frequencies exist. So when the stimulus contains high-frequency energy, little effect of alternating polarity would be observed. It means that the performance of any polarity method is related to the characteristics of the stimulus signal (its energy distribution in the frequency domain). However, this is not the case for patients with high-frequency hearing loss. The reason is that the hearing loss removes the typical high-frequency neural dominance, so lower frequency regions contribute more to eliciting the response.

Furthermore, some studies reported that the latency differences of click ABRs between rarefaction and condensation increased as the cochlear hearing loss increased [36]. Therefore, it can be inferred that the effects of alternating polarity would be more evident in patients with high-frequency hearing loss than in normal-hearing subjects, so alternating

polarity may not be appropriate for these patients regardless of what type of stimulus is used. Besides, it is worth noting that we tested the effects of the Sum polarity method on the ABR in normal-hearing subjects for the first time, which is a prerequisite for understanding its effects in hearing-impaired patients.

5. Conclusions

In summary, the proposed the Sum polarity method, which considers the physiological differences between positive and negative polarity stimuli on the auditory system. We compared the waveform morphology and latencies of the ABRs evoked by the familiar stimuli (including click, tone-burst, and chirp) between the Sum polarity and the conventional polarity methods in normal-hearing subjects. The experimental results showed that alternating polarity of the click and chirp stimuli has little effect on the ABR. In contrast, alternating polarity affected the ABR to low-frequency tone-burst, with the effect decreasing as the stimulus frequency increased. This conclusion indicated that the performance of any polarity method depends on the characteristics of the stimulus signal itself, and no polarity method is optimal for all types of stimuli. We suggested the optimal polarity selection for each stimulus type commonly used for evoking the ABR. Importantly, we verified the feasibility of the Sum polarity method, which provides another choice for eliminating stimulus artifacts in an evoked potential acquisition. In future work, we will further examine the effectiveness of the Sum polarity method and the applicability of the recommendations for optimal polarity selection in hearing-impaired subjects.

Author contributions

YJ conducted the experiments and wrote the first draft of the paper. MGA analyzed the data. OWS revised the manuscript. SC provided the experimental platforms. GL supervised the whole research.

Ethics approval and consent to participate

The data were obtained with the informed consent of all participants. The institutional review board of the Shenzhen Institutes of Advanced Technology, Chinese Academy of Sciences approved this research, code SIAT-IRB-190615-H0352.

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Conflict of interest

The authors declare no conflict of interest.

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