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Effect of Cephalic Versus Noncephalic Electrode Montage on the Amplitude-Modulated Frequency-Following Response

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Abstract

Background: The frequency-following response (FFR) is an auditory electrophysiological response that reflects the spectrotemporal characteristics of an acoustic stimulus with high fidelity. Electrode montage has a significant impact on the recorded response, likely because it influences the neural generator contributions. However, the relationship between montage configuration, especially the location of the inverting electrode, and FFR parameters remains unclear. This study aimed to investigate the effect of cephalic versus noncephalic inverting electrode placements on FFR characteristics in adults. Clarifying this relationship can help optimize montage selection for improving the clinical and research application of FFR recordings.

Methods: In this cross-sectional study, FFRs were recorded from 38 healthy adults (11 men, 27 women; mean age = 21.8 ± 2.3 years). Five amplitude-modulated tones with modulation frequencies of 85, 100, 115, 130, and 145 Hz were used. The responses were recorded simultaneously with 2 electrode montages of the vertex to ipsilateral mastoid (cephalic) and the vertex to the seventh cervical vertebra (noncephalic), and their amplitudes, phase values, and residual noises were measured and compared using independent sample t tests and repeated measures analysis of variance.

Results: The results showed roughly similar amplitudes (85 Hz: $P = 0.541$, 100 Hz: $P = 0.867$, 115 Hz: $P = 0.511$, 130 Hz: $P = 0.774$, 145 Hz: $P = 0.608$), while significantly different noise (85 Hz: $P = 0.526$, 100 Hz: $P = 0.244$, 115 Hz: $P = 0.022$, 130 Hz: $P = 0.003$, 145 Hz: $P = 0.071$) and phase values (85 Hz: $P = 0.720$, 100 Hz: $P = 0.002$, 115 Hz: $P = 0.001$, 130 Hz: $P = 0.001$, 145 Hz: $P = 0.704$) were observed between the 2 electrode montages. Moreover, the noncephalic montage exhibited lower between-subject variability.

Conclusion: The results demonstrated that both electrode montages could be reliably used for recording FFR. However, noncephalic montage may offer practical advantages in clinical and research contexts due to reduced variability and improved response consistency, thus enhancing the diagnostic accuracy and efficiency of auditory assessments.

Keywords: Frequency-Following Response, Electrode Montage, Cephalic, Noncephalic, Neural Generator

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Introduction

Frequency-following response (FFR) is an auditory electrophysiological response that can be evoked by multiple acoustic stimuli, including speech, modulated tones, and musical sounds (1, 2). Different terminologies have

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↑What is "already known" in this topic:
Research shows that FFR originates mainly from the auditory cortex, brainstem, and auditory nerve. Electrode montage configuration and stimulus features influence their relative contributions. However, studies report conflicting results regarding the effect of electrode montage orientation on FFR recordings.

→What this article adds:
This study clarifies how cephalic and noncephalic electrode montages affect FFR characteristics. It highlights the advantage of noncephalic montage in reducing variability and enhancing signal consistency, contributing to more reliable FFR recordings for clinical and research purposes.

been used for this response. We used the same as suggested by Kraus et al. (3) in this study. In recent years, a growing body of research has been published about FFR, showing a trending interest in research employing this response. FFR can be produced by complex stimuli like speech, rich in time and frequency composition. Hence, it is richer in terms of spectrotemporal features compared to auditory brainstem response (ABR), which is typically evoked by simpler stimuli like clicks and tone bursts (1, 4, 5). As a result of its richness and unique fidelity to spectrotemporal features of acoustical stimuli, FFR appears to be a potential tool for investigating the neurophysiological processing of sounds in the central auditory nervous system (CANS) (1, 6). FFR has been used for objective validation of auditory interventions such as hearing aid fitting and auditory training (7). However, before FFR can be standardized as a clinical test, it is essential to understand the influence of various contributing factors, such as electrode montage, which may affect the neural generators involved and thereby alter spectrotemporal response features.

Evoked electrophysiological responses are recorded concerning the spatial arrangement of neural dipoles within the auditory system (8). Extracellular ionic and voltage changes caused by action and postsynaptic potentials in a neural population develop dipoles. Dipoles can be recorded using a minimum of 2 electrodes under appropriate conditions. Provided there is a suitable alignment of the dipole and synchronous spatial summation of neuronal voltage changes, an electrical field is formed and volume-conducted toward the scalp surface (9). This volume conduction process depends both on the features of the dipole (as mentioned before) and the resistance and conductance of the medium between the dipole and the skin (9). For optimal recording of each dipole, the electrodes must be correctly positioned in alignment with the dipole's orientation.

The neural generators of FFR have been studied by various researchers (10-14). Based on prior studies, the auditory nerve, brainstem, and auditory cortex are considered to be the 3 main generators. The relative contribution of each generator varies depending on factors such as electrode montage and the modulation frequency (MF) of the evoking acoustic stimulus. Generally, the brainstem is regarded as the principal source of FFR (14). Amplitude-modulated (AM) tones with MFs up to 2000 Hz are commonly used in research to investigate FFR's neural origins. As MF increases, the response is believed to originate from more peripheral auditory structures.

Different electrode montages have been used to record FFR, including vertex to the nape of the neck, vertex to the ipsilateral mastoid, vertex to the seventh cervical vertebra (C7), ipsilateral mastoid to contralateral mastoid, and forehead to ipsilateral mastoid (1, 2, 12, 15). Since brainstem dipoles are oriented along a frontocentral axis, vertical electrode montages match this orientation best (9, 16). As a result, such montages are expected to yield larger response amplitudes. However, there have been controversies in prior studies; some studies support this assumption, while others do not. One explanation for these inconsistencies could be the recording of common responses by both inverting and noninverting electrodes. Ideally, the signal should be captured only by the noninverting electrodes, with the common noise being recorded by both electrodes and subtracted in the differential preamplification unit. Although in practice, when both electrodes are placed in a cephalic position, some of the desired responses can be recorded by both electrodes (17). This issue is less likely with a noncephalic placement, such as the nape of the neck or C7.

A study conducted by Purcell et al analyzed group delays calculated from FFRs elicited by AM stimuli with sweeping MF (18). Their results indicated that with increasing MF, the phase of the responses shifted, suggesting a shift in neural generators toward more peripheral auditory regions. In the cephalic electrode montage (vertex to ipsilateral mastoid), whether inverting and noninverting electrodes record FFR from the same or different neural generators, can result in the same or different response delays. In the first condition, this in-phase response would reduce the final response. However, if they record from different sources with a fixed delay difference, the phase relationship between the electrodes may vary with MF, leading to constructive or destructive interference. To explore this phenomenon further, this study used a narrow range of different MFs, similar to the method proposed by King et al (15). This narrow range of MF would almost prevent contribution from cortical neural generators and keep the delay difference constant. This way, it would be possible to investigate the neural generators recorded by inverting and noninverting electrodes. This study aimed to investigate the effect of a spatial array of electrode montage and the effect of inverting the electrode's place on the amplitude and neural generators of FFR.

Methods

Participants

In this cross-sectional study, 38 (11 men, 27 women) adults with normal hearing, aged 18 to 30 years (mean age = 21.8 ± 2.3 years), participated in this study. Before the main test, conventional pure tone audiometry (250 to 8000 Hz) and tympanometry were performed on participants to verify normal hearing (<20 dB HL in audiometry) and normal middle ear function (tympanogram type An) (19), respectively. In addition, ABR was performed using a click stimulus with 80 dB nHL intensity, and all participants had normal wave V latencies and morphology. All participants had a negative history of otologic or neurologic disease. This study's process was approved by the Medical Ethics Committee of Iran University of Medical Sciences.

Stimulus

Five AM stimuli with a carrier frequency of 576 Hz and MFs of 85, 100, 115, 130, and 145 Hz, each with a duration of 140 msec, were designed using MATLAB (MathWorks). These parameters were similar to the method used by King et al. (15). To avoid distortion of stimuli, modulation depth was set to 90%. Furthermore, a 20-msec

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rise/fall time was applied to the stimuli using the linear fade-in/fade-out function of Audacity software. The final stimulus file was imported into the Biologic Navigator Pro device. The stimuli amplitudes were calibrated to 85 dB SPL using a B&K 2250 L sound level meter.

Stimuli were delivered monaurally to the right ear using the 2-channel Biologic Navigator Pro, with a rate of 4.1/sec and with alternating polarity. The recording window was set to 170.67 msec, including a 17 msec prestimulus time window, which resulted in a 73.23 msec interstimulus interval. Each stimulus was presented up to 2000 times (sweeps) to ensure signal averaging and reduce noise. Online filtering was set to 30-2000 Hz to inhibit low-frequency noises and aliasing of high-frequency components. The order of stimulus presentation was randomized across participants.

Recording

Cephalic and noncephalic electrode montages were used to record responses. The assignment of device channels to each montage was randomized among participants. In both electrode montages, the noninverting electrode was placed on the vertex, and the ground electrode was placed on the forehead. For the inverting electrode, the C7 was used for the noncephalic montage, and the ipsilateral mastoid was used for the cephalic montage. Ag/AgCl electrodes were used at all sites, and impedance differences were kept below 2 kΩ throughout the testing period. Participants were instructed before the examination to sit on a chair and relax while watching a silent movie during the examination. During the experiment, the electroencephalography (EEG) noise level was carefully monitored, and the response was repeated if it was contaminated by excessive noise caused by the participant's occasional movements.

Response Analysis

Data points of the responses were extracted and analyzed using MATLAB (MathWorks). Before performing the fast Fourier transform (FFT) on responses, the Hanning window was applied to the responses to prevent frequency leakage. The selected time window of 170.67 msec (from available options of the recording device) would lead to a bin width of 5.85 Hz, slightly far from the desired bin width of 5 Hz. To address this, the zero padding method (1) was applied to extend the window to 200 msec, yielding a bin width of exactly 5 Hz. FFT was then performed on the responses, and both amplitude and phase values were recorded. Furthermore, the residual noise of responses was calculated by measuring the amplitude in the 17-msec prestimulus interval. Subsequently, the response waveforms were visually inspected to confirm the signal presence, and waveforms with poor morphology were omitted in both electrode montages.

Statistical Analysis

All data were statistically analyzed using IBM SPSS 21. The distribution of all data was proven to be normal using the one-sample Kolmogorov-Smirnov test. Independent sample t tests were carried out to compare the amplitude and phase of FFR between cephalic and noncephalic electrode montages in each MF. Repeated measures analysis of variance (ANOVA) was performed to compare the differences in amplitudes across MFs. Statistically significant values were set at $P < 0.05$.

Results

Figure 1 shows the grand average and individual waveforms of responses in the time domain. As shown in the picture, overall, the responses demonstrate good replicability, particularly for MFs above 85 Hz. Additionally, the variability of responses seems to be less in noncephalic electrode montages.

Figure 2 shows the grand average and individual spectra of the responses in the frequency domain. As illustrated in this figure, the amplitude peaks can be found in frequency ranges of 1-50 Hz, corresponding to MF, and harmonics of MF. Greater spectral variability is seen in the cephalic montage responses compared to the noncephalic montage.

Figure 3A shows the mean FFR amplitudes obtained from both electrode montages. Independent sample t tests were used to compare amplitudes between the 2 montages in each frequency. As shown in this figure and revealed by statistical results, there was no significant difference in any frequencies (85 Hz: $P = 0.541$, 100 Hz: $P = 0.867$, 115 Hz: $P = 0.511$, 130 Hz: $P = 0.774$, 145 Hz: $P = 0.608$).

Figure 3B shows the mean phase values of FFRs recorded with both electrode montages. The same statistical process was used to compare phase values. The results revealed a significant difference between phase values of cephalic and noncephalic electrode montages in frequencies of 100, 115, and 130 Hz (100 Hz: $P = 0.002$, 115 Hz: $P = 0.001$, 130 Hz: $P = 0.001$). However, no significant difference was defined in frequencies of 85 and 145 Hz(85 Hz: $P = 0.720$, 145 Hz: $P = 0.704$).

The repeated measures ANOVA was performed to compare the differences in amplitudes of the 2 montages between frequencies. The results of the Mauchly test of sphericity established sphericity ($P = 0.095$), and thus no significant difference was found.

The variances of amplitude and phase values between the 2 electrode montages were compared using the Levene test for equality of variances. As shown in Tables 1 and 2, the variances of amplitudes in frequencies of 100 and 145 Hz were not equal. Unequal variances were also reported for phase values in frequencies of 85, 100, and 115 Hz. The remaining frequencies of amplitude and phase had equal variances in both electrode montages.

The residual noise of the 2 electrode montages was compared using independent sample t tests (shown in Figure 3C). Significantly higher levels of noise were found for noncephalic electrode montage in frequencies of 115 and 130 Hz (115 Hz: $P = 0.022$, 130 Hz: $P = 0.003$). This difference was not significant in remaining frequencies (85 Hz: $P = 0.526$, 100 Hz: $P = 0.244$, 145 Hz: $P = 0.071$).

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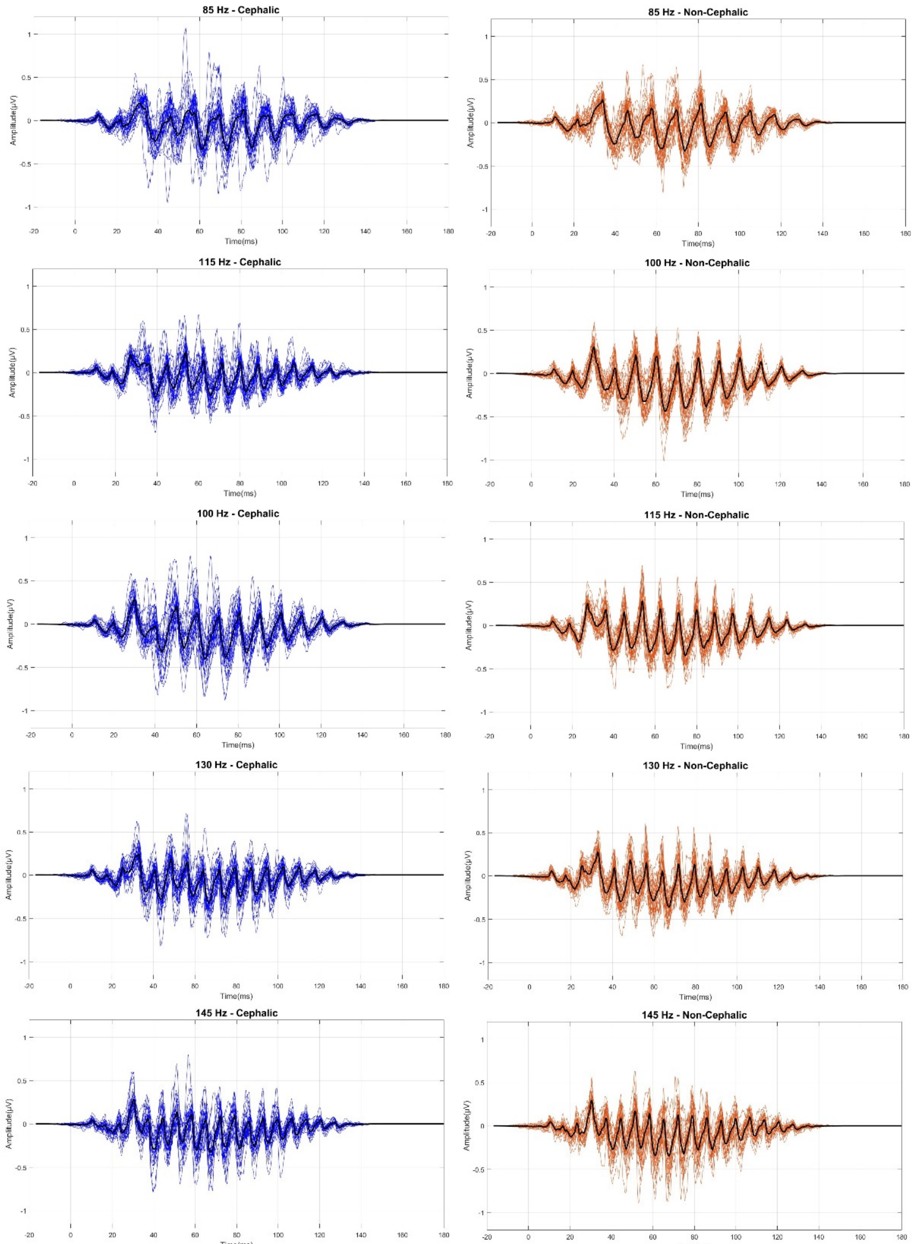

Figure 1. The grand average (thick line) and individual waveforms (thin lines) of FFRs recorded in the cephalic (left column) and non-cephalic(right column) electrode montages in frequencies of 85, 100, 115, 130, and 145 Hz.

Discussion

In this study, we aimed to compare amplitudes and phase values between cephalic and noncephalic electrode montages. Based on the results, no significant differences were found in the amplitude of FFRs evoked by 5 stimuli with MFs of 85, 100, 115, 130, and 145 Hz between cephalic and noncephalic electrode montages. This is consistent with the results of the Easwar et al study (20), finding no significant effects of the electrode montage (vertex to mastoid versus vertex to the neck) on FFR's amplitude and noise.

We hypothesized that the absence of significant amplitude differences between the 2 electrode montages could be due to 2 reasons. First, as indicated in previous research, variations in electrode orientation can influence the tracking of neural dipoles, potentially resulting in amplitude differences. However, in both our study and that of Easwar et al, the orientation differences between montages were relatively minor, unlike those in studies by King et al. (15, 21) and Urichuk et al. Second, the slightly higher noise level observed in the noncephalic montage may have contributed to reduced amplitudes. In our experience, this increased noise is closely related to participants' head

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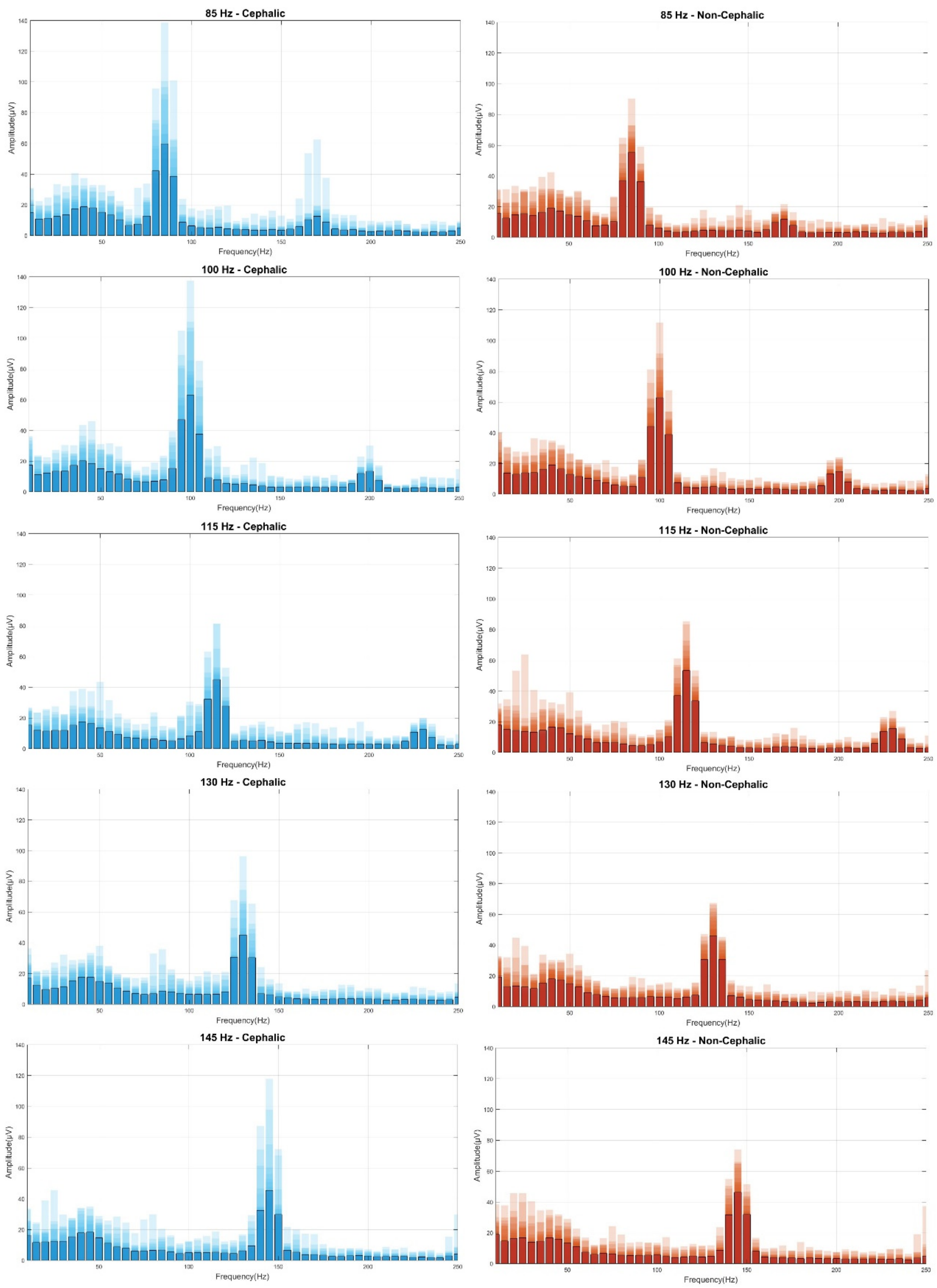

Figure 2. The grand average(solid colour bars) and individual spectrums(shadow bars) of FFRs recorded in the cephalic (left column) and non-cephalic(right column) electrode montages in frequencies of 85, 100, 115, 130, and 145 Hz.

and neck posture and likely stems from muscular activity in the neck area, which cannot be fully eliminated through response averaging (22). Notably, this higher noise in the noncephalic electrode montage is inconsistent with the results of Easwar et al's study (20), possibly due to differing noise measurement methods. While Easwar et al calculated residual noise using the mean value of bins surrounding the MF, our study used the amplitude of the prestimulus interval.

The phase values of FFRs differed significantly between electrode montages. Prior studies suggest that FFRs are generated by multiple neural sources, with some dominating based on stimulus characteristics and recording conditions (7, 14). It appears that with the settings of this study, both electrode montages record roughly the same main neural generators, although there may be slight differences in volume conduction or contributions from secondary neural generators. More studies are needed to investigate

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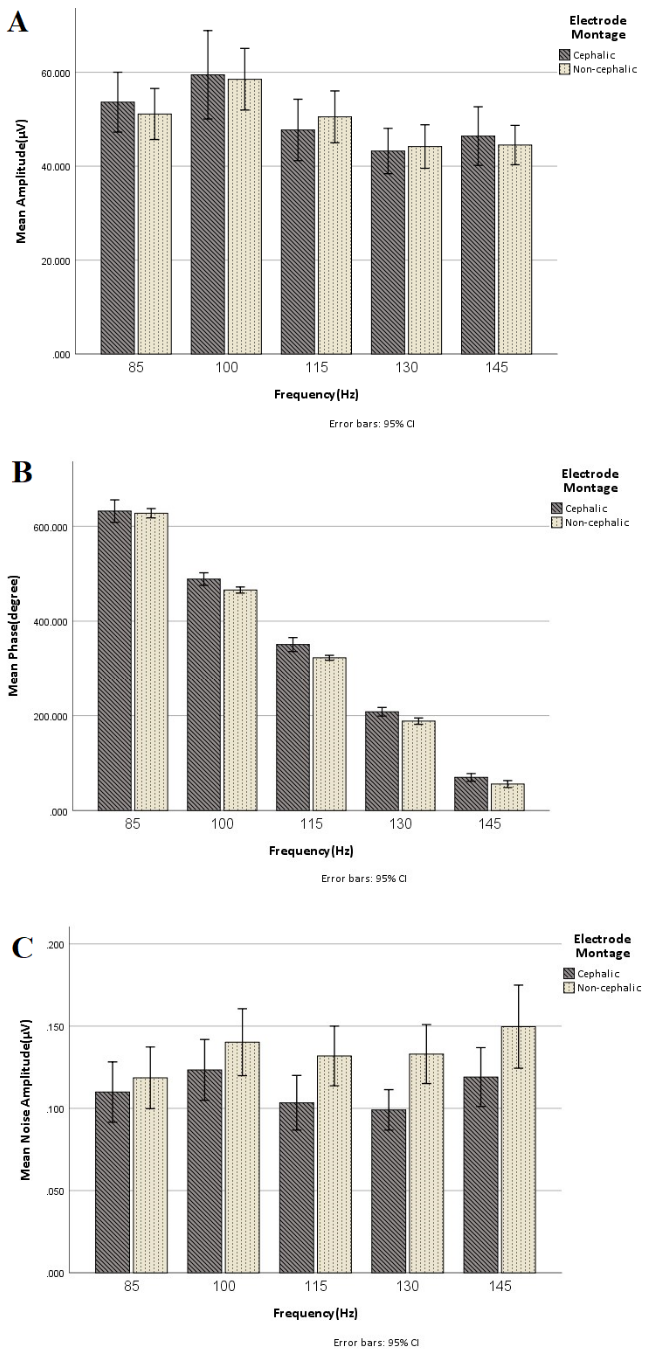

Figure 3. Bar charts showing mean (A) amplitude, (B) phase, and (C) residual noise levels of FFRs recorded using cephalic and non-cephalic electrode montages at modulation frequencies of 85, 100, 115, 130, and 145 Hz. The vertical black line on each bar shows a 95% confidence interval.

this hypothesis using a sweep of MF in a broader range and with better control of environmental noises. Testing during sleep may also be beneficial, as sleep does not affect FFRs evoked by MFs above 100 Hz.

Our results showed no significant differences in FFR amplitudes between the 2 montages across different frequencies. Along with the earlier finding of nonsignificant amplitude differences at each frequency, this may indicate a dominant contribution from the noninverting (vertex) electrode in the cephalic montage. As discussed in the "Introduction" section, the differences in amplitudes of FFR between electrode montages across MFs could reflect the recording of shared or distinct FFRs' neural generators by inverting and noninverting electrodes. Although we observed some variability in amplitude differences between montages across frequencies, these differences were

Table 1. Results of Levene's test for equality of variances for amplitudes of FFR in the following frequencies

Frequency (Hz)	F	Df1	Df2	*P*- value
85	0.305	1	68	0.582
100	4.049	1	72	0.048*
115	0.304	1	70	0.583
130	0.007	1	70	0.936
145	6.429	1	72	0.013*

* Statistically significant

Table 2. Results of Levene's test for equality of variances for phase values of FFR in the following frequencies

Frequency (Hz)	F	Df1	Df2	*P*- value
85	4.454	1	66	0.039*
100	10.415	1	68	0.002*
115	18.321	1	68	0.000*
130	3.149	1	68	0.080
145	0.508	1	68	0.479

* Statistically significant

not statistically significant. It can be suggested that the response is predominantly recorded by the noninverting electrode (vertex), while the inverting electrode (ipsilateral mastoid) records a weaker response from common and distinct neural generators. Investigating the effect of MF on FFR parameters was not a primary goal of this study. However, as shown in Figure 3, phase values exhibit an inverse relationship with MF. The relationship between MF and both FFR amplitude and residual noise appears more complex. Future studies should explore this relationship using a broader range of MFs.

Finally, amplitude and phase values recorded with the noncephalic montage showed generally lower variances, indicating reduced between-subject variability. This finding suggests that the noncephalic montage may be advantageous in studies aiming to distinguish between test conditions more clearly. Lower variability enhances the reflection of neural activity and improves differentiation in both clinical and research settings. Lower variability may also lead to a narrower normative range, enhancing the clinical utility of FFR.

Conclusion

Both cephalic (vertex to ipsilateral mastoid) and noncephalic (vertex to C7) electrode montages can be reliably used to record FFR. While their amplitudes are comparable, the noncephalic montage shows significantly lower between-subject variability. Additionally, in the cephalic electrode montage, the response is dominantly recorded by the noninverting electrode (vertex), while the inverting electrode (ipsilateral mastoid) seems to record weaker responses from common and separate neural generators.

Authors' Contributions

Mohammad Sadegh Khatami: Conceptualization, methodology, data collection, and writing the original draft; Hassan Haddadzade Niri: Conceptualization, methodology, supervision, and writing, reviewing, and editing; Nariman Rahbar: Statistical analysis, writing, reviewing, and editing.

Ethical Considerations

This study's process was approved by the Medical Ethics Committee of Iran University of Medical Sciences. All subjects were obtained informed written consent before participating in this study.

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Conflict of Interests

The authors declare that they have no competing interests.

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