Hearing Research 465 (2025) 109344

Contents lists available at ScienceDirect

Hearing Research

journal homepage: www.elsevier.com/locate/heares

Technical note

On the definition and implications of stimulus polarity for the recording of ocular vestibular evoked myogenic potentials

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ARTICLE INFO

Keywords:
Ocular vestibular evoked myogenic potentials
Stimulus polarity
Bone-conducted vibration
Transducer
B250
Condensation
Rarefaction

ABSTRACT

Objective: This study investigates the effects of mastoid stimulus polarity on the recording of bone-conducted ocular vestibular evoked myogenic potentials (oVEMPs). The goal was to analyze how different stimulus polarities, specifically condensation and rarefaction, influence the amplitude and latency of oVEMP responses.
Methods: Monocyclic sinusoidal tone bursts at 250 Hz and 500 Hz were used to stimulate the vestibular system in 21 participants with normal hearing and normal vestibular function. The stimuli were delivered through a B250 transducer in both condensation and rarefaction polarities. The output force waveforms were measured with an artificial mastoid and the time derivative of the force were calculated as surrogate for the jerk. For the different stimulus polarities and respective signal output, i.e., acceleration and jerk, the resulting oVEMP responses were compared.
Results: Rarefaction stimuli generally produced clearer and larger n1-p1 responses compared to condensation stimuli. A pre-response n1 peak was observed for 250 Hz condensation stimulation, while 500 Hz condensation stimulation showed a secondary p1 peak following the main response. The output force and jerk, as recorded on an artificial mastoid, suggest that the inwards-directed force of the condensation phase is crucial for eliciting the oVEMP response.
Conclusion: Stimulus polarity plays a critical role in the measurement of bone-conducted oVEMPs, affecting both the timing and magnitude of the response and should thus be always checked and reported. For mastoid stimulation the most effective jerk for oVEMP recordings was achieved by rarefaction stimulation.

1. Introduction

Vestibular receptor function can be measured by eliciting cervical and ocular vestibular-evoked myogenic potentials (cVEMPs (Colebatch et al., 1994), oVEMPs (Rosengren et al., 2005). Air conducted sound (ACS) as well as by bone conducted vibration (BCV) activate predominantly irregular saccular and utricular afferents, and thus the mainly ipsilateral inhibitory vestibulocollic reflex (cVEMP) or the mainly contralateral excitatory vestibuloocular reflex (oVEMP) (Curthoys and Dlugaiczyk, 2020).

BCV is normally used to elicit the appearance of the n10 wave under the eye contralateral to the stimulated ear (referred to as oVEMP) but is also feasible to evoke cVEMP responses especially when air conduction in the middle ear is impaired, e.g. in conductive hearing loss or patients with implantable hearing devices (Fröhlich et al., 2022). It is generated by various types of bone conduction (BC) transducers. These include audiometric BC transducers, e.g., B81 (Radioear, New Eagle, USA), large vibratory shakers such as the Mini-Shaker 4810 (Brüel & Kjær Sound & Vibration Measurement A/S, Copenhagen, Denmark) or tendon hammers (Hecker et al., 2014). Most recently, the B250 transducer was developed and is a powerful low-frequency device for generating VEMP responses (Fredén Jansson et al., 2024, 2021; Håkansson et al., 2018).

It has been shown that VEMP responses depend on stimulus frequency, amplitude, and phase as the physical properties of the stimulus

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https://doi.org/10.1016/j.heares.2025.109344
Received 27 March 2025; Received in revised form 12 June 2025; Accepted 23 June 2025
Available online 26 June 2025

as well as stimulation site. Air-conduction induced oVEMPs appeared with a shorter latency with rarefaction stimulation as compared to condensation (Amorim et al., 2017), while also the opposite was reported for BC stimulation (Cai et al., 2011; Jombik et al., 2011). In particular, BC tone bursts applied to the forehead which start with the tip of a Mini-Shaker accelerating toward the head had shorter latency than those in which the initial acceleration direction is away from the head (Burgess et al., 2013).

In some experiments a “double-peak” appeared as first oVEMP response when the stimulation polarity was inverted (Cai et al., 2011; Jombik et al., 2011; Lim et al., 2013; Romero et al., 2019). It was concluded that a negative to positive change of the stimulus, i.e., an initial condensation force was crucial for eliciting VEMP responses. This was also observed in AC stimulation where a condensation stimulus signature provided the largest response amplitude (Romero et al., 2019).

Govender et al. (2016a) reported that stimulus phase did not affect either amplitude or latency in an AC cVEMP human trial. Reanalyzing data from Lim et al. (2013) stimulus onset phase was described to affect the cVEMP latencies but not the amplitude. For oVEMP, rarefaction stimuli led to an earlier response, while a larger amplitude was measured for condensation stimuli (Govender et al., 2016b).

Beside physical properties and acceleration directions, studies in different animal species have shown that different stimulus phases activated different primary afferent units in the otoliths and could thus be specifically elicited by inverted stimulus polarity (Amorim et al., 2017). An observed significant decrease of n1 with increasing rise-time is consistent with the hypothesis that the n1 component is caused by activation of jerk-sensitive irregular primary otolithic afferents (Burgess et al., 2013).

For test signals of short duration, stimulus polarity is clearly defined on an engineering level (389–6:2007–10, 2007). The standard is applied for signals with a duration of <200 ms including clicks. Condensation and rarefaction are defined as force waves causing an over-force or under-force relative to the static force at the plane of the output port of the transducer. However, in combination with ramp functions, fading or transient phenomena, the maximum force can differ among BC transducers.

For calibration of short duration signals, the root-mean-square value of a long-duration sinusoidal signal with the same peak-to-peak value is used and reported as peak-to-peak equivalent vibratory force level (peVFL). For VEMP recordings, “0–1–0″ tone bursts are used, i.e., with a transducer input that consists of one cycle of the waveform, meaning one plateau with zero rise and fall time. This is the negative to positive change of the stimulus (peak-to-peak), which differs in the time domain from the positive to negative change of the same stimulus.

In this report we focus on the implications of stimulus polarity and definitions for the recording of bone-conducted oVEMPs with the B250 transducer at the mastoid.

2. Material and methods

Sinusoidal tone-bursts with frequencies of 250 and 500 Hz were generated using the Eclipse EP25 system (Interacoustics A/S, Middelfart, Denmark). The selection of these frequencies was made on the basis that BCV resulted in larger n10 responses at these low frequencies (Burgess et al., 2013), which are utilised clinically (Cai et al., 2011; Zhang et al., 2012). Bursts consisted of one cycle without fading ramps (0–1–0) and were delivered in condensation and rarefaction onset following the ISO 389 definition (389–6:2007–10, DIN, 2007). The signals were delivered to a B250 transducer (Håkansson et al., 2018) placed on an artificial mastoid 4930 (Brüel & Kjaer Sound & Vibration Measurement A/S, Copenhagen, Denmark) with a static force of 5.4 N, and output force was recorded with an InfiniiVision 2000 X-Series oscilloscope (Keysight, Santa Rosa, USA). Force output vectors $\mathbf{F}(t)$ and their gradients with respect to time ($d\mathbf{F}(t)/dt$) as correlate of the jerk were analyzed. The B250 transducer was driven directly by the Eclipse EP25 without any intermediate power amplifier.

For comparison with physiological responses oVEMP recordings from a group of 21 normally hearing participants without vestibular or neurological disorders were used. Participants were sitting and asked to look up approximately 30° during B250 bone-conduction stimulation at the right mastoid with trains of the above-mentioned tone bursts with a rate of 8 Hz and an amplitude of 135 dB peak-to-peak equivalent vibratory force levels (peVFL). Therefore, the stimuli were calibrated on an artificial mastoid 4930 (Brüel & Kjaer Sound & Vibration Measurement A/S, Copenhagen, Denmark).

It is important to point out that all BCV transducers (B250, B81, and Minishaker) may produce an arbitrary polarity (+ or −) of the output force due to their internal design (e.g., wiring) and there might even be a 180 degrees phase shift of the signal pathway of the test system itself, i.e., when the signal is measured by the artificial mastoid or in subsequent preamplifier and oscilloscope presentation. It is therefore of utmost importance to verify that a first positive force stimulus according to the condensation definition (inward the pad of the artificial mastoid) delivered from the test station (clinical system) really gives a first positive force cycle at the artificial mastoid pad as seen in the oscilloscope monitoring the voltage output. It is advisable to first check the polarity of the measuring system simply by pressing, e. g. with the fingertip, towards the rubber pad to confirm that a press results in a positive peak in the presentation on the oscilloscope.

Self-adhesive Neuroline 720 surface electrodes (Ambu A/S, Ballerup, Denmark) were used to record the EMG signals. They were placed on the infra-orbital ridge 1 cm below the lower eyelids after the skin had been prepared to provide impedances of <5 kΩ. VEMP responses were recorded with the Eclipse EP25 system from the ocular muscles contralateral to the stimulated side with a reference electrode on or just above the nasion (Scherer et al., 2024).

The study protocol was reviewed and approved by the ethics committee of the Medical Faculty of Martin Luther University Halle-Wittenberg and the University Hospital Halle (approval number: 2024–032). The study was performed in accordance with the ethical standards of the Declaration of Helsinki. Written informed consent was obtained from all participants before inclusion to this study.

Data processing was performed with MATLAB software (The MathWorks, Natick, USA). At least 200 artifact-free electromyographic (EMG) epochs were recorded, bandpass filtered between 10 and 1000 Hz, and averaged according to the stimulation condition. Mean oVEMP response curves were calculated as average across all participants and further referred to as “grand average”. The output force and jerk waveforms of the transducer were compared to the grand average oVEMP responses for rarefaction and condensation stimulation.

3. Results

Fig. 1 shows the grand average oVEMP responses for 250 Hz and 500 Hz stimulation. For both stimulus frequencies, clear n1-p1 oVEMP responses were observed. The latencies of n1 and p1 amplitudes of the grand average waveforms as well as the individual amplitudes are summarized in Table 1. For 250 Hz condensation stimulation, a pre-response was observed (labelled PR in Fig. 1) with a latency of 9.6 ms and an amplitude of −3.1 μV. For 500 Hz condensation stimulation, no pre-response but a second peak after the p1 response was observed with a latency of 15 ms and an amplitude of 2.6 μV.

The output force of the B250 transducer varied between rarefaction and condensation voltage input. The frequency of the sinusoidal burst was reflected in both output amplitudes. After onset of a 250 Hz stimulus, the force output was increasing which is reflected by a rising envelope. The maximum amplitude was achieved at the second and third half-cycles, outwards-directed first for rarefaction, inwards-directed first for condensation. For 500 Hz tone bursts, the maximum force was achieved in the second half-cycle. For rarefaction stimulation, the maximum inwards directed amplitude was the second inwards-directed

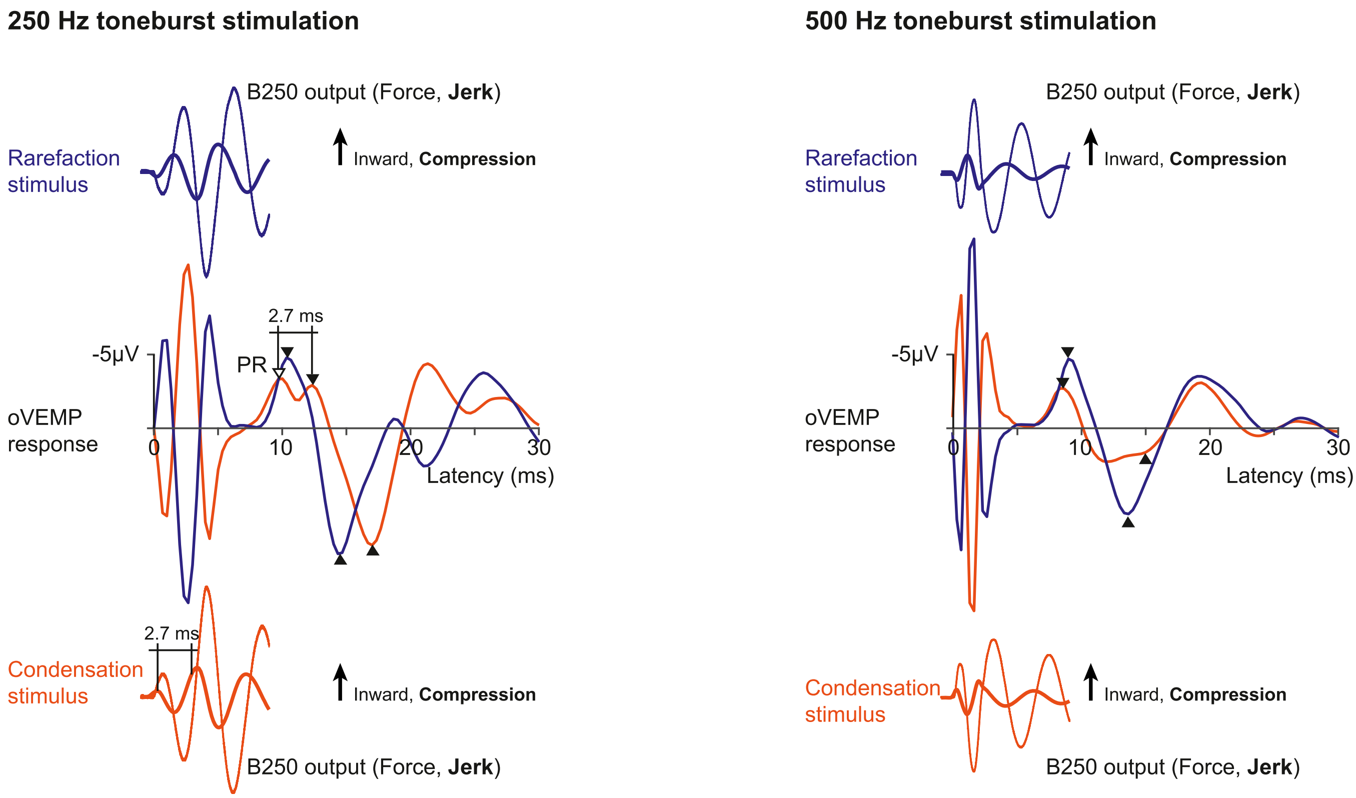

Fig. 1. Bone-conducted oVEMP response waveforms for 250 Hz (left) and 500 Hz (right) condensation (orange) and rarefaction (blue) toneburst stimulation. The stimulus sinusoidals are displayed as force (thin lines) and force derivative with respect to time (jerk, bold lines) at an artificial mastoid for rarefaction (top row, blue) and condensation (bottom row, orange). A clear n1-p1 response is observed with a pre-response (PR) peak for 250 Hz - condensation.

Table 1
Means, standard deviations and 95 % confidence intervals (CI) of oVEMP amplitudes and latencies for the different stimulus polarities and burst frequencies.

Burst frequency	Stimulus polarity	Grand average n1 latency / ms	Mean n1 amplitudes (SD) and 95 %CI / μV	Grand average p1 latency / ms	Mean p1 amplitudes (SD) and 95 %CI / μV
250 Hz	Condensation	12.3	−4.95 (2.51) [−6.13,−3.78]	17.0	9.08 (4.46) [7.04,11.1]
250 Hz	Rarefaction	10.3	−6.40 (4.08) [−8.26,−4.54]	14.3	9.25 (5.17) [6.89,11.6]
500 Hz	Condensation	8.3	−4.71 (4.47) [−6.86,−2.55]	12.0	5.12 (4.03) [3.29,6.95]
500 Hz	Rarefaction	9.0	−7.40 (5.48) [−9.90,−4.91]	13.7	10.36 (6.97) [7.10,13.62]

force peak. For condensation stimulation, the first inwards-directed force peak occurred in the first half-cycle and a second peak in the third half-cycle, both with amplitudes below the maximum output force in the second half-cycle (directed outwards). The first inwards directed force peak was larger for rarefaction than for condensation stimuli. A long-lasting ringing of amplitudes was observed for both polarities. The output frequency of the first cycle was 315 Hz for the 250 Hz stimulus (cycle time 3.17 ms) and 465 Hz (cycle time 2.15 ms) for the 500 Hz stimulus.

The time signal of the jerk is also displayed in Fig. 1 and reflects the change of force by time. Due to the fading of the force amplitudes, the jerk curves were different to a simple phase-shift of the amplitude curve. The extreme values of the jerk curves are about at the time points at which the force amplitude crosses the zero line. This behavior was more pronounced with 500 Hz stimulation as compared with 250 Hz stimulation.

Fig. 1 also shows the connection between the jerk curves and the occurrence of the oVEMP n1 response. For 250 Hz condensation stimulation, the time difference between the pre-response peak and the actual n1 oVEMP response was 2.7 ms and almost the same as the time difference between the first and second inwards-directed jerk peaks (compression). For 250 Hz, the n1 oVEMP response for condensation was measured about 2 ms later than for rarefaction and corresponded to the time difference between the first inwards-directed jerk peaks of the respective force gradients (1.6 ms). For 500 Hz, the first inward-directed jerk peak for condensation was larger than for 250 Hz and occurred 1 ms earlier. Also, the oVEMP n1 peak for condensation was about 1 ms earlier than for rarefaction.

4. Discussion

The results show that stimulus polarity influenced the bone-conducted oVEMP response when using the B250 BC transducer for stimulation. Both, latencies and amplitudes were changed by switching from condensation to rarefaction. A condensation polarity induced a pre-response waveform for 250 Hz stimulation and an overall reduced n1-p1 amplitude for both, 250 Hz and 500 Hz stimulation as compared with the more effective rarefaction stimulation. Fig. 1 shows that for the

B250 transducer, the output force waveform differed a lot from the input sinusoidal burst. The length of the first cycle was reduced for 250 Hz stimulation (3.17 instead of 4 ms) and a little increased for 500 Hz (2.15 instead of 2 ms). The present oVEMP results refer to mastoid stimulation but could also differ for transducer placement on the forehead because of the different orientation of the stimulation force with regard to the otolith organs.

We assume that not the amplitude of the transducer force but rather the jerk as rate of change of force per second of the stimulation is important for achieving a fast acceleration of the head and thus the excitation the otolith sensor cells. This is consistent with the animal observations that the otolith organs act as jerk detectors (Curthoys et al., 2019). For rarefaction, the first negative, i.e., outward movement of the transducer is only very small because of the inertia of the oscillating mass. The following inwards movement, however, is much larger and stronger than the first inwards movement with condensation. Since the jerk reflects the rate of change of the force with respect to time, the oVEMP response latencies are rather in phase with that gradient than the actual force amplitude. Due to the slow fading of the force amplitudes (ringing), the jerk curves are somehow different compared to a simple phase-shift of the amplitude curve. As depicted in Fig. 1, the pre-response peak using a condensation stimulus occurred about 2.7 ms before the actual n1 response and can be explained by the jerk waveforms. For 500 Hz stimulation, the latency difference of the n1 responses followed the time difference of the corresponding compression jerk peaks between the different stimulation polarities.

Thus, a clear reporting of the polarity of the used stimuli following the standards (389–6:2007–10, DIN, 2007) is important for achieving reliable oVEMP results in clinical diagnostics. It is important to note that fading bursts with larger frequencies can lead to very little elongations of the first waveforms and the polarity could hardly be interpreted from the artificial mastoid output.

Since the wiring of the B250 like other bone conduction devices, is not standardized, it may differ from one transducer to the next. The same stimulus voltage applied to different transducers would thus cause exactly oppositely directed movements and so opposite stimuli. This wiring inconsistency was important when the devices were used for simple bone conduction audiometry using long duration stimuli, where stimulus onset was not crucial. However, in the case of oVEMPs, it is the initial movement of the device which is crucially important in initiating the response, so the exact wiring is of utmost importance.

In clinical diagnostics, oVEMP amplitudes are often reported as amplitude asymmetry ratios between right and left side (Rosengren et al., 2019). Thus, it is crucial to assure equal stimulation polarities between the sides to avoid amplitude cancelling.

The influence of stimulus polarity on the oVEMP responses could vary with the stimulation amplitude. In the present data, the force amplitude was just above the threshold level but rather low. If the stimulus amplitude increases, the first inwards deflection of the condensation stimulus would increase as well and could induce an oVEMP response as well at the latency at which the pre-response peak was observed otherwise. The stimulus amplitude, however, should be kept as low as possible to avoid hearing risks for the patients.

We conclude that stimulus polarity is important for measuring bone-conducted oVEMPs and should be checked in every clinical and research setting using an artificial mastoid and an oscilloscope. The medial-lateral force towards the otoliths is the effective stimulation (jerk), the polarity of which may differ from the polarity at stimulus onset due to slope effects and thus determines the actual latency of the n1-p1 response waveforms. Because the design of the B250 does not generate a simple unidirectional movement of the tip according to the voltage polarity, the terms rarefaction and condensation are rather technical and do not directly implicate jerk polarity. In terms of clinical efficacy, the polarity for the B250 which generates the largest oVEMP n1 is here referred to as rarefaction in case of mastoid stimulation.

CRediT authorship contribution statement

Torsten Rahne: Writing – original draft, Visualization, Validation, Supervision, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Hannah Schütz:** Writing – review & editing, Validation, Investigation. **Julia Dlugaiczyk:** Writing – review & editing, Methodology. **Laura Fröhlich:** Writing – review & editing, Methodology. **Karl-Johan Fredén Jansson:** Writing – review & editing, Methodology. **Bo Håkansson:** Writing – review & editing, Methodology.

Data availability

Data will be made available on request.

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