COMPARISON OF AIR-CONDUCTION AND BONE-CONDUCTION OCULAR VESTIBULAR EVOKED MYOGENIC POTENTIAL RECORDINGS USING INFRA-ORBITAL AND BELLY-TENDON ELECTRODE MONTAGES

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CERTIFICATE

This is to certify that this dissertation entitled **"Comparison of air conduction and bone conduction ocular vestibular-evoked myogenic potential recordings using Infraorbital and Belly-Tendon Electrode Montages"** is a bonafide work submitted as part of fulfilment of the degree of Master of Science (Audiology) of the student with Registration Number P01II24S023025. This has been carried out under the guidance of a faculty of this institute and has not been submitted earlier to any other university for the award of any other Diploma or Degree.

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DECLARATION

This is to certify that this dissertation entitled **"Comparison of Air-Conduction and Bone-Conduction Ocular Vestibular Evoked Myogenic Potential Recordings using Infra-orbital and Belly-tendon Electrode Montages"** is the result of my own study under the guidance of Dr. Niraj Kumar Singh, Associate Professor in Audiology, Department of Audiology, All India Institute of Speech and Hearing, Mysuru and has not been submitted earlier to any other university for the award of any other Diploma or Degree.

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ABSTRACT

Vestibular evoked myogenic potentials (VEMPs) are widely used to assess otolith organ function and the utriculo-ocular pathway. The response characteristics of oVEMP are influenced by several stimulus and recording parameters, including the mode of stimulation and electrode montage. The present study aimed to investigate the effect of electrode montage on the response parameters of oVEMP elicited using air-conduction (AC) sound and bone-conduction (BC) vibration in healthy adults. Fifty clinically healthy adults aged 18–30 years participated in the study. Contralateral oVEMPs were recorded simultaneously using belly-tendon (BT) and infra-orbital (IO) electrode montages during AC and BC stimulation. A 500-Hz tone burst stimulus was used for both AC and BC stimulation. AC and BC stimuli were delivered through insert earphones and B-71 bone vibrator, respectively. Recordings were obtained in a sitting position with an upward gaze angle greater than 30 degrees. Response rate, absolute latencies of n1 and p1 peaks, peak-to-peak amplitude, and inter-aural asymmetry ratio (IAAR) were analysed. The BT montage yielded significantly higher response rates and larger peak-to-peak amplitudes than the IO montage for both AC- and BC-oVEMP recordings ($p < 0.05$). No significant differences in n1 and p1 latencies were observed between the montages for most comparisons ($p > 0.05$). The BT montage demonstrated significantly lower IAAR for both modes of stimulation than the IO montage ($p < 0.05$). Comparison between stimulation modes showed that AC-oVEMP generally produced higher response rates and larger amplitudes than BC-oVEMP, particularly with the IO montage. Overall, the findings suggest that the BT electrode montage provides more robust and reliable oVEMP recordings than the conventional IO montage for both AC and BC stimulation and may therefore be preferred in clinical applications for improved response acquisition.

Chapter I

Introduction

Hearing is one among the five vital senses that the humans are blessed with, and ear is the specialised organ responsible for hearing. While hearing is an important function of the ear, this is not the only function it performs. The sensory part of the ear, the inner ear, processes not only the sound waves but also helps maintain the balance of the body. Maintenance of body balance is ensured through the integrity of the vestibular system and its connections to the central nervous system.

The vestibular system includes three semicircular canals (lateral, anterior, & posterior) and two otolith organs (saccule & utricle). Together, they play an important role in maintaining balance and postural stability during linear and angular accelerations as well as during the tilts and translation. Dysfunction within this system can lead to symptoms such as dizziness, vertigo, imbalance, and impaired gaze stability, all of which significantly affects an individual's quality of life. Timely use of a battery of tests helps assesses the functioning of these systems. While there are several tests such as Rotary Chair Test (RCT), Bithermal Caloric Test (BCT), Video Head Impulse Test (vHIT), etc., that assess the functioning of the semicircular canals, there is paucity of tools to assess the otoliths' function. A widely used clinical test to assess the functioning of the otolith organs is the vestibular evoked myogenic potential (VEMP). In fact, VEMP is one of the only few tests for utricular assessment (Rosengren et al., 2005; Curthoys & Vulovic, 2011) and the only test of saccular assessment (Colebatch et al., 1994).

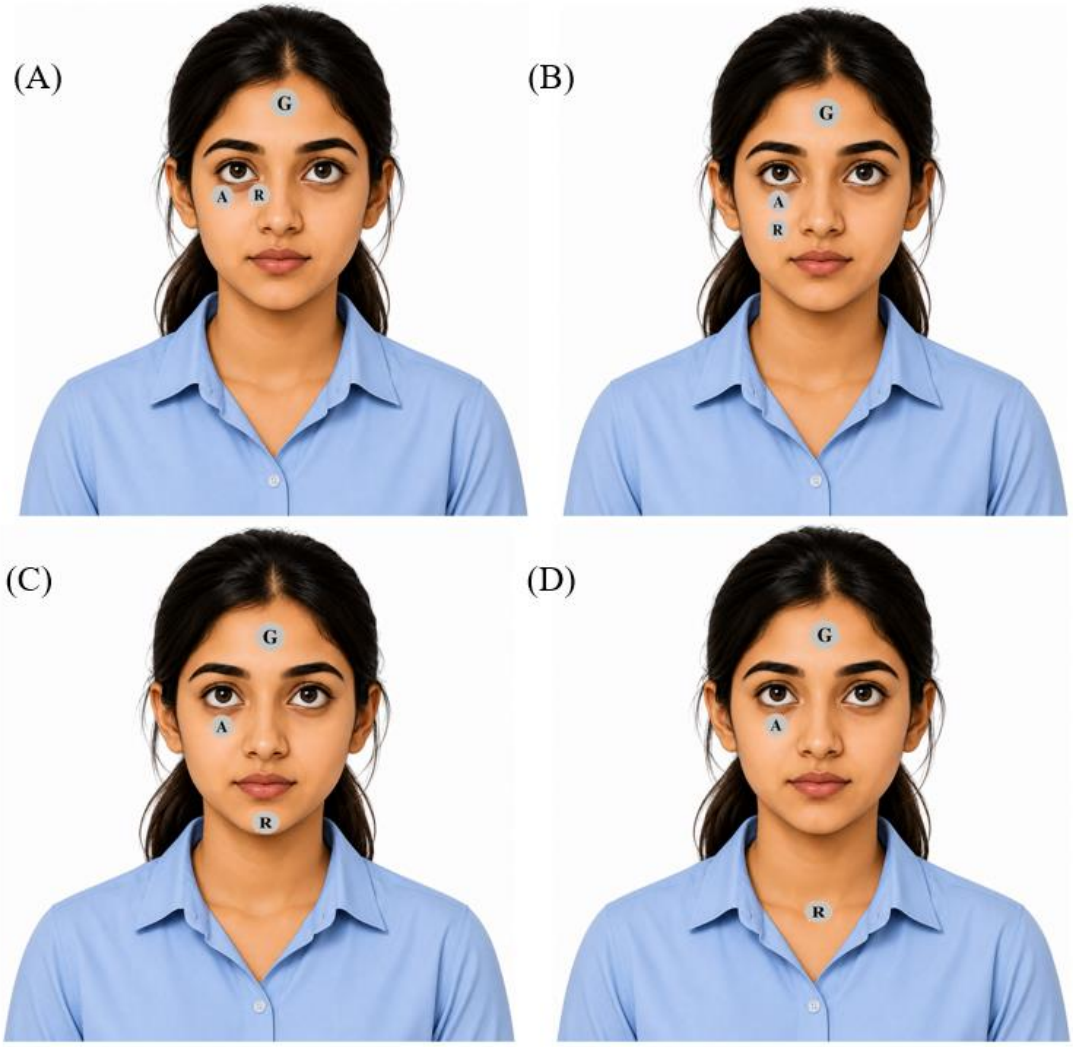
VEMPs are short-latency electromyographic potentials elicited in response to high intensity air-conduction sound (AC), bone-conduction (BC) vibration, and galvanic stimulation (Rosengren et al., 2010; Kim & Oh, 2014; Camis & Creed, 1930). VEMP can be recorded from several muscles in the body; the two major clinical types, cervical VEMP (cVEMP) and ocular VEMP (oVEMP), are recorded from the surface electrodes placed over the sternocleidomastoid muscle (Colebatch et al., 1994) and the inferior oblique muscle (IOM) (Rosengren et al., 2005), respectively.

oVEMP assesses the functional integrity of the utriculo-ocular pathway. The potentials generated within the utricle travel through the superior vestibular nerve to reach the medial longitudinal fasciculus, where it decussates and ends at the inferior oblique muscle via the oculomotor nuclei and ocular nerve (Curthoys, 2019; Welgampola et al., 2009; Weber & Rosengren, 2015). Using surface electrodes placed over the inferior oblique muscle, an oVEMP waveform containing a negative peak (n1 or n10) around 8-12 ms, followed by a positive peak (p1 or p15) around 13-18 ms is recorded (Todd et al., 2007).

For several years, the studies on oVEMP have used the inferior orbicular (IO montage). This electrode montage involves the positioning of active and reference electrodes below the centre of the lower eyelids at a distance of 1 cm and 3 cm, respectively. However, the IO montage does not always produce a 100% response rate even in clinically healthy young adults (Li et al., 2015). Therefore, in the pursuit of identifying an electrode montage capable of better recording of oVEMP than the traditional IO montage, recent studies have explored alternate electrode montages. These electrode montages include belly-tendon (BT) (the active electrode below the lateral canthus referenced to an electrode below the medial canthus), chin-referenced (CR) (the active electrode positioned at the same place as in the IO montage referenced to an electrode on the chin) and sternum-referenced (SR) (the active electrode positioned at the same location as in the IO montage referenced to an electrode on the sternum) (Raveendran & Singh, 2026). Figure 1 shows a representation of various electrode montages used for recording oVEMP.

Figure 1

Various electrode montages used for recording oVEMP



Note. (A) belly-tendon montage; (B) infra-orbital montage; (C) chin-referenced montage; (D) sternum-referenced montage; ‘G’: ground electrode; ‘R’: reference electrode; ‘A’: active electrode

The results of the studies comparing two or more electrode montages show a unanimous agreement in favour of the use of BT montage over the modern-day clinically used IO montage. They showed higher response prevalence, larger peak-to-peak amplitude, and excellent test–retest reliability, both in clinically healthy individuals and individuals with vestibular symptoms when using the alternate electrode montages than the IO montage

(Raveendran & Singh, 2024, 2026; Mat et al., 2023), suggesting the necessity to replace the IO montage with BT montage in the routine clinical practice.

1.1 Need for the study

oVEMPs can be elicited using different stimuli; however, the activation pattern and the response parameters may vary among them (Welgampola et al., 2005; Todd et al., 2007). Studies have shown that in comparison to the air-conduction stimuli, the bone-conduction stimulation results in increased response prevalence, larger amplitude in pathological ears (Wang et al., 2010; Fröhlich et al., 2021), and lower asymmetry (Rosengren et al., 2011). Similarly, a change in stimulus polarity was found to significantly influence the latencies of BC-oVEMP but not AC-oVEMP (Iwasaki et al., 2007; Sudhakar, 2015), thereby demonstrating a differential effect of the AC and BC modes of stimulation on oVEMPs. Therefore, it appears reasonable to believe that the stimulation modes may potentially affect even other oVEMP response parameters differently, which highlights the importance of considering stimulation modes in clinical decision-making.

It was discussed in the previous section that electrode montage significantly alters the response characteristics of oVEMP, and that the BT electrode montage produces the largest response amplitude among the known electrode montages used for recording oVEMP. However, the above mentioned findings are applicable when the oVEMP is obtained using the conventional IO montage, and when obtained using air-conduction stimuli. It is little known whether the superiority of BT montage is maintained when obtained using the BC stimulus. In fact, the studies on montage superiority have shown equivocal findings for the BC mode of stimulation. Vanspauwen et al. (2017) compared, among others, the BT and IO montages on 14 clinically healthy individuals using a minishaker at the Fz position as the stimulus. In their study, the BT montage yielded significantly larger peak-to-peak amplitudes and higher response rates compared to the IO montage, while the latencies remained comparable between the two montages. Additionally, they also showed better inter-rater reliability and lower inter-subject variability when BC-oVEMPs were obtained using the BT montage than the IO montage. In contrast, Ansari (2025) observed no significant difference in response parameters between the IO and BT montages for the BC stimulation mode. While several differences between these two studies could be the reason for the differences in the findings between them, the precise reason for the differences is not known. Additionally, differences in findings exist only between the studies using BC stimulation for eliciting the oVEMP. There is a unanimous agreement on BT being the best among the electrode montages used for recording AC-oVEMP. Therefore, the difference could also be caused by the differential effect of the mode of stimulus presentation, akin to the differences described above. However, no study has, to the best of our knowledge, obtained oVEMPs to AC and BC stimulation from the same participants to understand whether the differences in findings between AC and BC modes exists due to differences in participant characteristics, mode of stimulation or any other factor that was also different between the set of studies using AC-oVEMP and BC-oVEMP. Therefore, there is a need for studies comparing the electrode montages for AC and BC stimulation in the same group of participants to clear some of the clouds concealing the true nature of the reason for the differences in findings among the studies.

1.2 Aim of the study

The present study aims to investigate the effect of electrode montage on oVEMP response parameters when elicited using air-conduction sound and bone-conduction vibration in healthy adults.

1.3 Objectives of the study

1. To compare the response rate, absolute latencies, peak-to-peak amplitude and inter-aural asymmetry ratio of BC-oVEMP between BT and IO electrode montages.

2. To compare the response rate, absolute latencies, peak-to-peak amplitude and inter-aural asymmetry ratio of AC-oVEMP between BT and IO electrode montages.

3. To compare the response rate, absolute latencies, peak-to-peak amplitude and inter-aural asymmetry ratio between AC-oVEMP and BC-oVEMP obtained using IO electrode montage.

4. To compare the response rate, absolute latencies, peak-to-peak amplitude and inter-aural asymmetry ratio between AC-oVEMP and BC-oVEMP obtained using BT electrode montage.

1.4 Null Hypothesis

1. There is no significant difference in the response rate, absolute latencies, peak-to-peak amplitude and inter-aural asymmetry ratio of BC-oVEMP between BT and IO electrode montages.

2. There is no significant difference in the response rate, absolute latencies, peak-to-peak amplitude and inter-aural asymmetry ratio of AC-oVEMP between BT and IO electrode montages.

3. There is no significant difference in the response rate, absolute latencies, peak-to-peak amplitude and inter-aural asymmetry ratio between AC-oVEMP and BC-oVEMP when obtained using IO electrode montage.

4. There is no significant difference in the response rate, absolute latencies, peak-to-peak amplitude and inter-aural asymmetry ratio between AC-oVEMP and BC-oVEMP when obtained using BT electrode montage.

Chapter II

Review of literature

Colebatch and colleagues in the year 1994 recorded the first VEMP using surface electrodes over the sternomastoid muscles in response to loud, brief clicks delivered through headphones. A biphasic positive-negative (p13-n23) response was recorded from electrodes placed over the muscle on each side. In 2005, Rosengren and colleagues reported oVEMP as a new vestibular evoked extraocular potential elicited by bone-conduction vibration, likely produced by synchronous activity in extraocular muscles (i.e., a myogenic potential). The evolution of research on the potentials confirmed that the oVEMP measures integrity of the utricule and superior vestibular nerve whereas the cVEMP measures the functionality of saccule and the inferior vestibular nerve (Manzari et al., 2012; Rosengren et al., 2010).

In addition to labyrinthine and neural pathologies, several studies have investigated factors that influence oVEMP response parameters, including stimulus characteristics, subject-related variables, and recording techniques. Studies have investigated VEMPs with different electrode placements and elicitation and acquisition parameters, using different modes of stimulation, such as air-conduction, bone-conduction, and galvanic stimulation (Rosengren et al., 2019).

Effect of electrode montages on oVEMP using AC stimulation

The placement of electrodes below the contralateral eye of the stimulated side is known to yield a more robust response in comparison to the ipsilateral side (Chihara et al., 2007, Murnane et al., 2011). Further, the choice of electrode montage is also known to affect the oVEMP's response parameters. Recent researchers have investigated the oVEMPs from different electrode montages such as belly-tendon (BT), chin-referenced (CR), sternum-referenced (SR), and infra-orbital (IO) montages and compared various response parameters between two or more of them (Raveendran & Singh, 2024, 2026). Table 2.1 summarises the critical stimulus and acquisition parameters of oVEMP used in the studies comparing AC-oVEMP from different montages and their primary outcome.

Table 2.1

Summary of studies comparing the response parameters of Ocular Vestibular Evoked Myogenic Potential to 500-Hz tone burst obtained using different electrode montages.

Study	Participants	Electrode montages	Intensity	Response filter (in Hz)	Findings
Sandhu et al. (2013)	16 ears	IO and BT	95 dB nHL	3-1000 Hz	Larger amplitude with BT montage than IO
Raveendran & Singh (2024)	55 young healthy adults	IO, BT, CR and SR	125 dB peSPL	1-1000 Hz	Significantly shorter latencies, larger amplitudes and higher SNR in BT than all others montages
Makowiec et al. (2019)	12 unilateral SCD ears and 36 age-matched control ears	IO and BT	95 dB nHL	-	BT montage yielded significantly larger amplitudes than IO montage in both population

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Study	**Participants**	**Electrode montages**	**Intensity**	**Response filter (in Hz)**	**Findings**
Piker et al. (2018)	19 normal adults	IO and BT	125 dB pSPL	10-1000Hz	BT montage produced significantly larger oVEMP amplitudes than the conventional IO montage
Raveendran & Singh (2026)	30 adults with ANSD and 30 age-matched controls	IO, BT, CR and SR	125 dB peSPL	1-1000 Hz	BT montage showed superior response characteristics in healthy adults and ANSD

Note. ‘IO’: infra-orbital; ‘BT’: belly-tendon; ‘CR’: chin-referenced; ‘SR’: sternum-referenced; ‘oVEMP’: Ocular Vestibular Evoked Myogenic Potential; ‘SNR’: signal-to-noise ratio; ‘SCD’: Semicircular Canal Dehiscence; ‘ANSD’: Auditory Neuropathy Spectrum Disorder

Across multiple studies, the researchers have shown that different electrode montages have effect on the oVEMP response characteristics. The reviewed studies consistently show that the BT montage yields larger amplitudes, higher response rates, and better signal-to-noise ratios than standard infra-orbital placements in both healthy individuals and clinical populations, suggesting possibility of replacing the IO montage with BT montage in the routine clinical practice.

Effect of electrode montages on oVEMP using BC stimulation

The different mode of stimulation affects the oVEMP response parameters. Air-conduction stimulation is the most commonly used mode; however, bone-conducted vibration has been shown to produce more robust responses, particularly in individuals with middle ear pathology. Bone-conduction stimulation results in higher response prevalence, larger peak-to-peak amplitudes, and lower inter-aural asymmetry compared to air-conduction (Rosengren et al., 2011; Fröhlich et al., 2021). However, the effect of BC mode of stimulation on oVEMPs obtained from different electrode montages have been explored sparingly.

Vanspauwen et al. (2017) investigated the effect of different electrode configuration for the oVEMP on 14 healthy subjects when bone-conducted vibration was used as the stimulus. The different electrode configurations were the IO, SR and nose-referenced (same as the BT montage) placements. They delivered the stimulus using a minishaker placed at Fz. The findings of the study showed larger amplitudes and higher response rates with BT montage than IO, or SR montages. They also observed better amplitudes with the SR montage than the IO montage.

In contrast, a recent study done by Ansari (2025) recorded BC-oVEMPs on 55 healthy adults using infra-orbital and belly-tendon electrode montages for mastoid and forehead stimulation separately. The responses from the two montages were acquired simultaneously using two channels of a dual channel VEMP recording system. The study found no significant difference between infra-orbital and belly-tendon electrode montage for either of the two places of stimulation.

The above review on the BC mode of stimulation shows that there exist discrepancies among the studies, which may be attributed to the different methodologies used. Therefore, there is a clear gap in literature as far as consensus on the optimal electrode montage for recording BC-oVEMPs is concerned.

Chapter III

Methods

3.1 Research design

The study used a quantitative within-subject experimental design. The oVEMP responses obtained using two different electrode montages were compared under two different modes of stimulation. Further, there was also comparison between the two modes of stimulation for each montage type.

3.2 Participants

The study included a group of clinically healthy individuals in the age range of 18 to 30 years. The sample size for the study was estimated using the G*Power 3.1 calculator (Faul et al., 2007). A sample size of 43 participants was found appropriate for the study when assuming an effect size of 0.5, based on the study by Vanspauwen et al. (2017), to achieve a statistical significance (α) of 0.05 and power (1-β) of 0.90. Hence, based on the above estimate, a total of 50 participants were recruited for the study, considering the possibility of any outliers that might be found during the statistical analysis.

3.2.1 Inclusion Criteria

- Normal hearing sensitivity (pure tone threshold ≤ 20 dB HL) at octave frequencies from 250 Hz to 8000 Hz for air-conduction and from 250 Hz to 4000 Hz for bone-conduction based on the World Health Organization criteria (WHO, 2021).
- SRT within ± 9 dB of the pure tone average.
- Speech identification scores (SIS) ≥ 90% for standard test material in the native language of the participants.

- Normal middle ear functioning as identified by an A/As type tympanogram with the presence of ipsilateral and contralateral acoustic reflexes at 100 dB HL for reflex eliciting tone of 1000 Hz.
- Loudness discomfort level > 100 dB HL for speech and tones.
- No retro cochlear lesion confirmed by conventional click-evoked auditory brainstem response elicited at two repetition rates (11.1/s & 90.1/s).
- No significant vestibular symptoms confirmed through the "SO STONED" questionnaire developed by Wuyts et al. (2016) administered in the form of an interview.
- No obvious abnormality on the functional screening tests of posture and equilibrium, such as the Romberg test, Fukuda stepping test (Unterberger test), Tandem gait test, Dysdiadochokinesia test, and Past-pointing test (finger-to-nose test).

3.2.2 Exclusion Criteria

- Known history of otological or neurological disorders.
- Presence of visual abnormalities (e.g., Diplopia) and/or oculomotor abnormalities.
- Presence of diabetes mellitus.
- Presence of hypertension.

3.3 Ethical consideration

The study got ethical approval from the Institutional Review Board (SH/IRB/M.4/AUD.40/2025-26) (Appendix I). The participants were informed about the study’s purpose and nature. All participants provided written informed consent prior to their enrolment in the study.

3.4 Test environment and instrumentation

The experiment was conducted inside a well-illuminated, sound-treated room with ambient noise levels within permissible limits (ANSI S3.1, 1991). A calibrated two-channel Neurosoft Neuro-Audio auditory evoked potential system (Version, 2010) with impedance-matched transducers, Radioear IP30 insert ear phone for air-conduction and Radioear B71 bone vibrator for bone-conduction, were used to record oVEMP responses.

3.5 Procedure

3.5.1 Procedure for the fulfilment of participant selection criteria

Otoscopic examination was done to check the status of the external auditory canal (EAC) and the tympanic membrane (TM). EAC inspection included checking for conditions such as cerumen impaction, otorrhea etc, whereas, the tympanic membrane inspection included the colour of the TM, abnormalities (bulging, perforation, etc.), and the presence or absence of normal landmarks (cone of light & manubrium).

The routine audiological evaluation included pure tone audiometry and speech audiometry. The pure-tone audiometric thresholds were obtained at octave frequencies from 250 Hz to 8000 Hz and 250 Hz to 4000 Hz for air-conduction and bone-conduction, respectively, using the modified Hughson and Westlake procedure (Carhart & Jerger, 1959). Speech audiometry included speech reception threshold (SRT) and Speech identification scores (SIS). These tests (SRT & SIS) were done using the standardised spondee word lists and phonetically balanced word lists, respectively, in the participant’s native language. Loudness discomfort level for speech was obtained through the standard instructions listed by the British Society of Audiology (2004).

Tympanometry was carried out with a probe-tone frequency of 226 Hz whose baseline intensity was maintained at 85 dB SPL. The air pressure in the external ear canal was varied from +200 daPa to -400 daPa. The same probe-tone frequency, along with the reflex eliciting signal of 1000 Hz, was used to examine the presence of ipsilateral and contralateral acoustic reflex in response a 100 dB HL stimulus.

Screening tools to check for posture and equilibrium such as Fukuda stepping test, Romberg test, Sharpened Romberg test, Past point test, Dysdiadochokinesis test and Tandem gait test were performed. For the Fukuda stepping test, participants were asked to stand at a fixed point and extend their arms in front of the body and march at the same place for 50 steps with eyes closed. Any deviation of 45° or more in any direction or 1 meter or more distance covered during the test were considered abnormal. For the Romberg test, the participants were asked to stand with eyes open and feet close together with each hand placed on the opposite shoulder. They were asked to maintain the same position while keeping the eyes closed for 30s. Presence of any significant sway during the eye-closed condition or inability to maintain balance in the eyes-closed condition for 30s were considered abnormal responses. During the Sharpened Romberg test, any noticeable postural sway or inability to maintain balance under the eyes-closed condition while standing with one foot in front of the other in a tandem stance position was considered indicative of postural dysfunction (Black et al., 1982). For the Past pointing test, the participants were asked to touch the finger tip of the examiner and then touch their own nose tip alternately, as fast as possible. The position of the clinician's finger was changed ensuring clear vision of the finger and easy reach. Presence of tremors and/or undershooting/overshooting of the target were considered abnormal responses. For the Dysdiadochokinesis test, the participants were asked to flip their palm in rapid alternation (supination & pronation) motion. Inability to rapidly flip the palm of hand alternately was considered an abnormal response. For the Tandem gait test, a straight line heel-to-toe walk was asked to be done, and deviation to any side or loss of balance were considered abnormal responses.

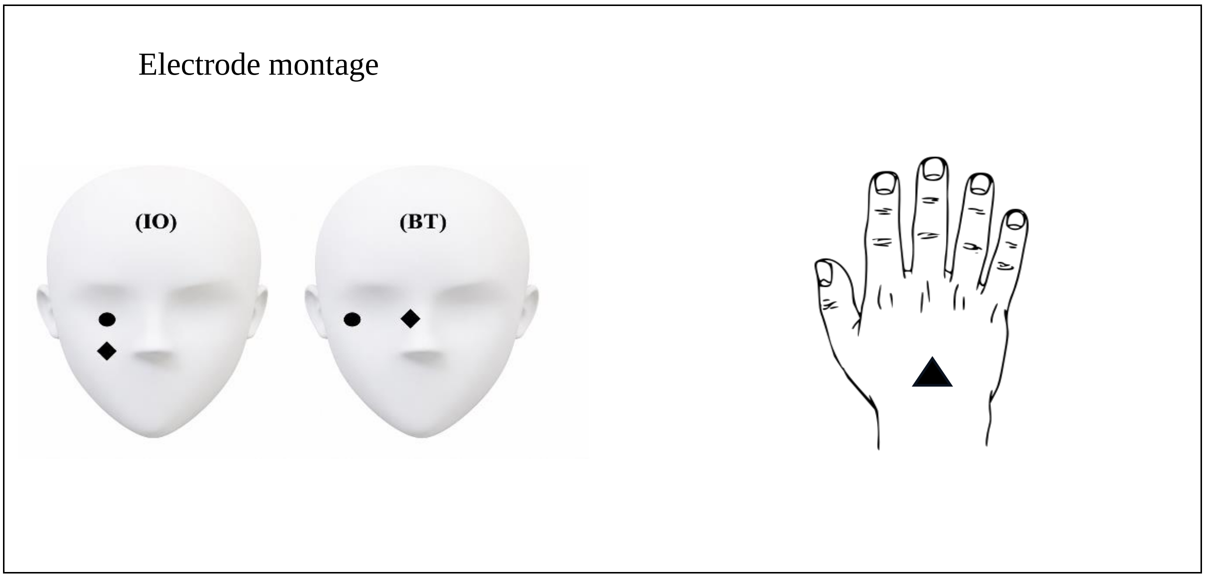
Auditory brainstem response (ABR) was used to rule out retro-cochlear pathology. The skin at the electrode placement sites were cleaned with an abrasive gel and 10-20 conduction paste was applied to enhance conductivity. The reference electrode was placed on the test ear's mastoid, the active electrode on the upper forehead, and the ground electrode on the contralateral ear’s mastoid. Click stimuli were delivered using rarefaction polarity. The stimulus delivery rates of 11.1/s and 90.1/s were used to present 1500 stimuli for each rate and the responses were band-pass filtered between 100 and 3000 Hz. The abnormality criteria on the basis of relative difference in latency between two peaks and amplitude ratio of wave V to I were used to classify the responses as indicative of a retro-cochlear lesion (Musiek et al., 1984).

3.5.2 Procedure for testing hypothesis

The contralateral oVEMPs were recorded using the IO and BT electrode montages simultaneously. For the IO electrode montage, the active electrode was placed on the infraorbital ridge, whereas the reference electrode was positioned on the cheek 2 cm directly below the active electrode. For the BT montage, the active and reference electrodes were positioned just below the lateral canthus (about 1.5 to 2 cm lateral from the orbital midline) and near the medial canthus, respectively. An electrode placed on the dorsum of the hand was used as a common ground electrode during the simultaneous recording using the BT and IO electrode montages. Figure 2 shows a representation of the electrode montages used in the present study. Before the recording, the electrode placement sites were gently scrubbed to ensure the absolute and inter-electrode impedance well within 5 kΩ and 2 kΩ, respectively. AC-oVEMP responses were elicited and recorded using the protocol used in a study by Raveendran & Singh (2024). The rarefaction polarity tone bursts of 500 Hz [intensity = 125 dB peSPL, rise-plateau-fall time = 2-2-2 cycle, repetition rate = 5.1 Hz] were used to evoke AC-oVEMPs. The analysis window was set to 70 ms. During the recording, the participants were asked to maintain a gaze elevation of 30º in the mid-sagittal plane and were further instructed to avoid eye blinks. The responses were band-pass-filtered between 0.1 Hz and 1000 Hz and amplified by a factor of 3000. A total of 200 averages were obtained per recording, and responses were acquired twice to ensure response replicability. A rest time of 1 minute or as per the participant's request was given to avoid fatigue and eye irritation. The BC-oVEMPs were obtained with the same stimulus and acquisition protocol as the AC-oVEMPs, except for the change in the transducer. The BC transducer was placed on the contralateral mastoid to the eye below which the electrodes were positioned.

Figure 2:

Schematic representation of infra-orbital (IO) and belly-tendon (BT) electrode montages used in present study.



Note: Filled circle represent active electrode; filled diamond represent reference electrode; filled triangle represent ground electrode

3.6 Measures

The obtained responses were analysed to identify absolute latencies of n1 and p1 peaks and the peak-to-peak amplitude. The inter-aural asymmetry ratio (IAAR) was determined using the Jonkee’s formula, which involves dividing the difference in peak-to-peak amplitude between the two ears’ recordings by their sum. This ratio was then multiplied by 100 to convert it into a percentage (Li et al., 1999; Singh & Barman, 2014).

$$\text{IAAR}=\frac{(\text{oVEMP amplitude of better ear}-\text{Amplitude of poorer ear})}{(\text{oVEMP amplitude of better ear}+\text{Amplitude of poorer ear})}*100$$

The response rate was calculated by counting the number of subjects or sides that showed a presence of biphasic response and was expressed as a percentage of the total number of subjects.

3.7 Statistical measures

Statistical analyses were done using IBM SPSS Statistics software for Windows, version 20.0 (IBM Corp., Armonk, NY, USA). Shapiro-Wilk's test of normality was used to examine the normality of data distribution to decide on the use of parametric or non-parametric statistical tools. The Shapiro-Wilk test revealed normal distribution for the absolute latencies and inter-aural asymmetry ratio (IAAR); therefore, paired-samples t-tests were used to compare these parameters between the electrode montages and stimulation modes. For the peak-to-peak amplitude, the data did not meet the assumptions of normality; so, Wilcoxon signed-rank test was used to compare them between the electrode montages and between the stimulation modes. For the response rate, the McNemar test was used to compare the proportion of present responses between the BT and IO electrode montages and between the AC and BC stimulation modes. Descriptive statistics, including the mean and standard deviation, were reported for normally distributed data, while the median and interquartile range were reported for non-normally distributed data. The level of significance was set at $p < 0.05$ for all comparisons.

Chapter IV

Results

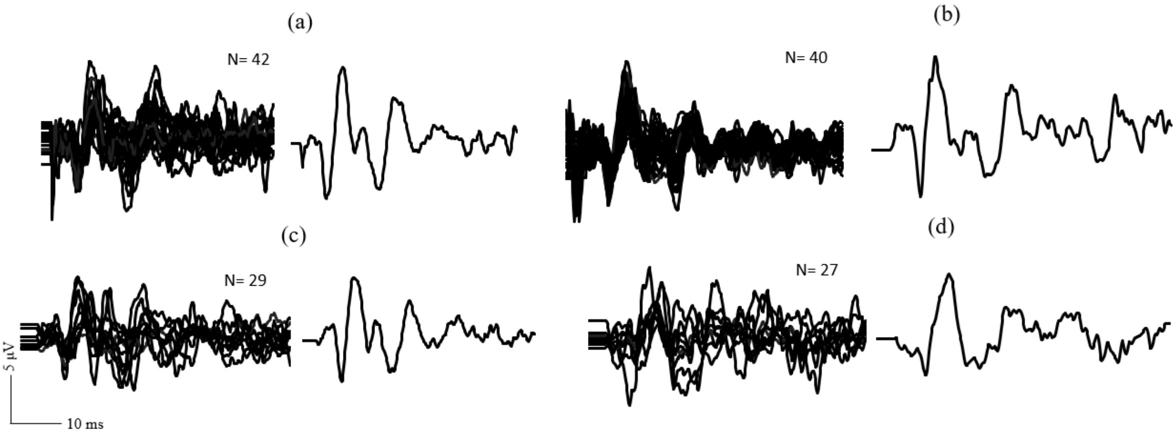
The present study was carried out to investigate the effect of electrode montage on oVEMP elicited by air-conduction (AC) and bone-conduction (BC) stimulation. The contralateral oVEMP responses were recorded from 50 healthy individuals using simultaneous recordings from belly-tendon (BT) and infra-orbital (IO) electrode montages during AC and BC stimulation. The outcomes of the statistical analyses for various response parameters, such as the response rate, absolute latencies of individual peaks (n1 & p1), peak-to-peak amplitude (n1-p1), and inter-aural asymmetry ratio (IAAR) for both electrode montages and both stimulation modes, are delineated below:

4.1 Comparison of various response parameters of BC-oVEMP between BT and IO electrode montages.

The contralateral oVEMPs in response to 500-Hz BC vibration were recorded simultaneously from the BT and IO electrode montages in each participant. Figure 4.1 shows the individual and grand-averaged oVEMP waveforms from the BT and IO electrode montages.

Figure 4.1

The Individual and Grand-averaged Waveforms of the Bone-Conduction Ocular Vestibular Evoked Myogenic Potentials from Belly-tendon and Infra-orbital Electrode Montages



Note. (a) Responses from Belly-tendon electrode montage to right ear stimulation; (b) Responses from Belly-tendon electrode montage to left ear stimulation; (c) Responses from Infra-orbital electrode montage to right ear stimulation; (d) Responses from Infra-orbital electrode montage to right ear stimulation; 'N': number of ears with a present oVEMP out of 50 ears.

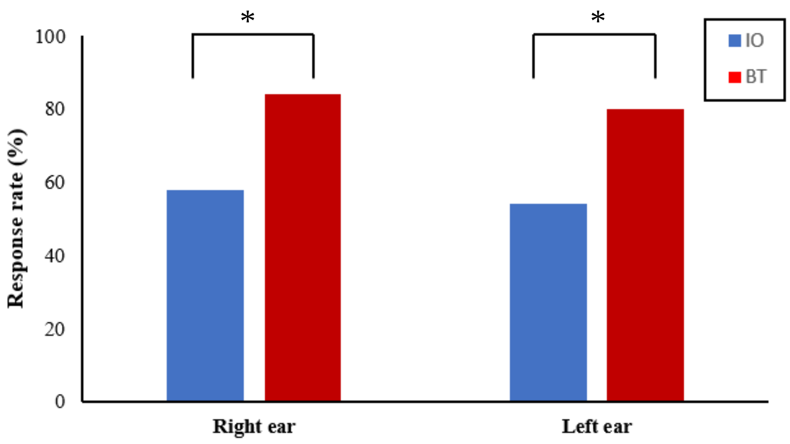
4.1.1 Comparison of the response rate of BC-oVEMP between the BT and IO electrode montages.

In response to the 500-Hz BC-vibration, oVEMPs obtained using the BT electrode montage were absent in 8 right ears and 10 left ears, resulting in response rates of 84% and 80%, respectively. However, oVEMPs obtained using the IO electrode montage were absent in 21 right ears and 23 left ears, resulting in response rates of 58% and 54%, respectively. On the statistical analysis, the results of the McNemar test revealed a significantly higher response rate with the BT electrode montage than with the IO electrode montage in right ear

($p < 0.001$) as well as left ear ($p < 0.001$). Figure 4.2 shows the comparison of the response rate of BC-oVEMP between the two electrode montages.

Figure 4.2

Response Rates of Bone-Conducted Ocular Vestibular Evoked Myogenic Potentials from Infra-orbital and Belly-tendon Electrode Montages, and the outcomes of McNemar Test for Comparison between the Montages



Note. 'BT': Belly-tendon electrode montage; 'IO': Infra-orbital montage; * indicates a significant difference between the montages ($p < 0.05$, McNemar test)

4.1.2 Comparison of the absolute latencies of BC-oVEMP between the BT and IO electrode montages.

The results of the Shapiro-Wilk's test of normality revealed normal distribution of absolute latencies of both n1 and p1 peaks' datasets of both the electrode montages ($p > 0.05$). Therefore, the descriptive statistical analyses were performed to obtain the mean and SD of the absolute latencies of oVEMP from both electrode montages. Table 4.1 shows the outcomes of the descriptive statistics.

Table 4.1

Mean and Standard Deviation of the Absolute Latencies of Individual Peaks (in ms) of Ocular Vestibular Evoked Myogenic Potentials Recorded from the Belly-tendon and Infra-orbital Electrode Montages

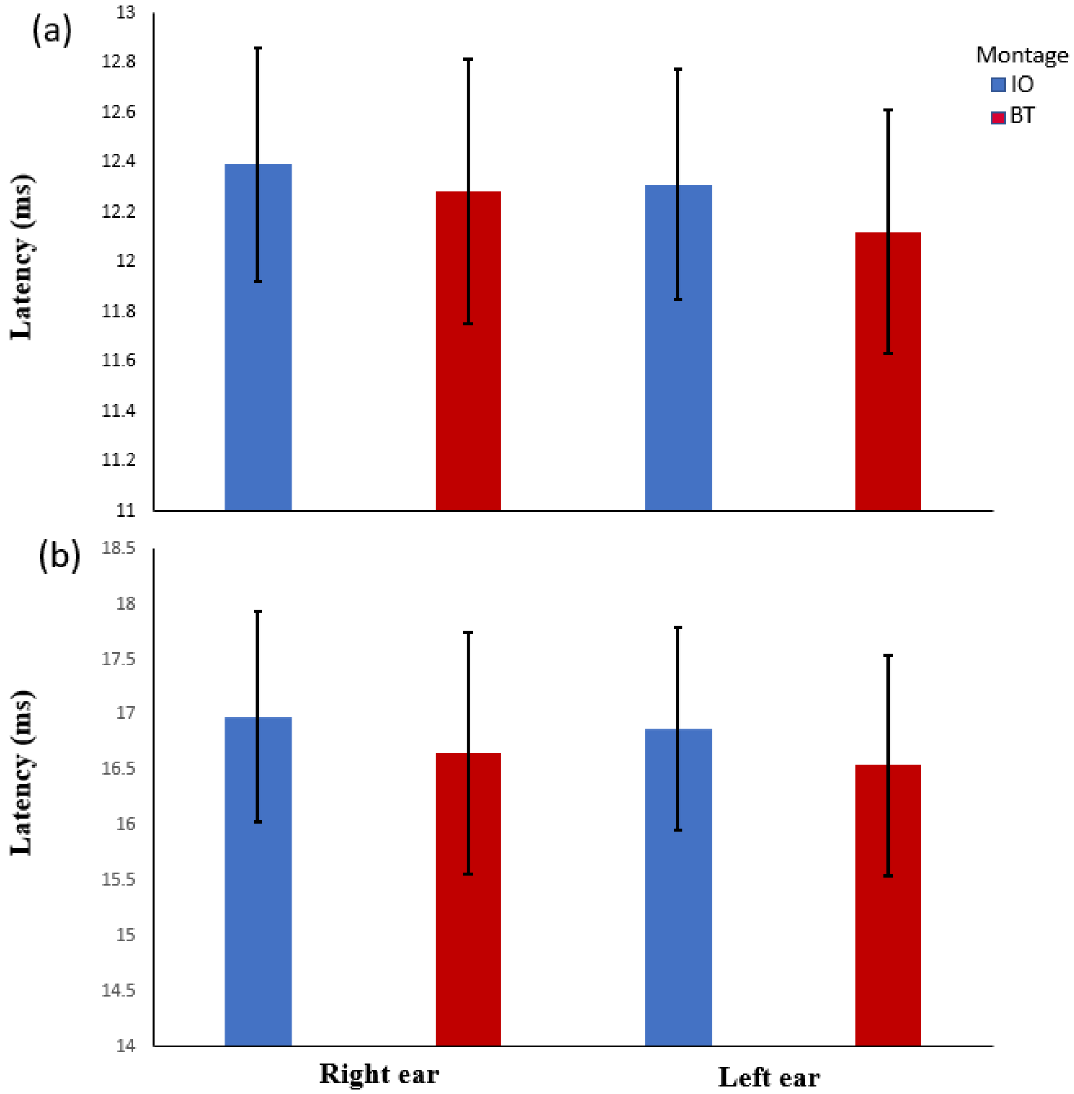
	Belly-tendon Montage				Infra-orbital Montage			
	Right ear		Left ear		Right ear		Left ear	
Parameter	N	M (SD)	N	M (SD)	N	M (SD)	N	M (SD)
n1 latency	42	12.28 (0.53)	40	12.12 (0.49)	29	12.39 (0.47)	27	12.31 (0.46)
p1 latency	42	16.65 (1.09)	40	16.54 (1.00)	29	16.98 (0.95)	27	16.87 (0.91)

Note. 'N': Number of ears with the presence of response out of 50 ears; 'M': mean; 'SD': standard deviation; the values within parentheses in the 'mean' column are of standard deviation

Paired samples t-tests were used to compare the latencies of BC-oVEMP between the BT and IO electrode montages. The results showed no significant difference in n1 latency between the electrode montages in right ear [t(28) = 0.780, $p = 0.442$] and left ear [t(26) = 0.253, $p = 0.802$]. Similarly, there was no significant difference in p1 latency between the electrode montages in right ear [t(28) = 0.475, $p = 0.639$] and left ear [t(26) = 0.253, $p = 0.802$]. Figure 4.3 shows the bar graph of n1 and p1 latencies of both electrode montages.

Figure 4.3

Absolute Latencies of n1 and p1 Peaks of Bone-Conduction Ocular Vestibular Evoked Myogenic Potentials from Belly-tendon and Infra-orbital Electrode Montages



Note. (a) n1 latency; (b) p1 latency; 'IO': infra-orbital; 'BT': belly-tendon; the height of the bar represents the mean whereas the whisker shows standard deviation; the height of the bar represents the mean whereas the whisker shows standard deviation

4.1.3 Comparison of the peak-to-peak amplitude of BC-oVEMP between the BT and IO electrode montages.

Following the finding of the violation of normality in the amplitude datasets ($p < 0.05$), descriptive statistical analyses were performed to obtain the median and interquartile range of the peak-to-peak amplitude of oVEMP from BT and IO electrode montages. Table 4.2 shows the outcomes of the descriptive statistics.

Table 4.2

Median and Interquartile Range of the Peak-to-peak Amplitude (in µV) of Ocular Vestibular Evoked Myogenic Potentials Recorded from the Belly-tendon and Infra-orbital Electrode Montages

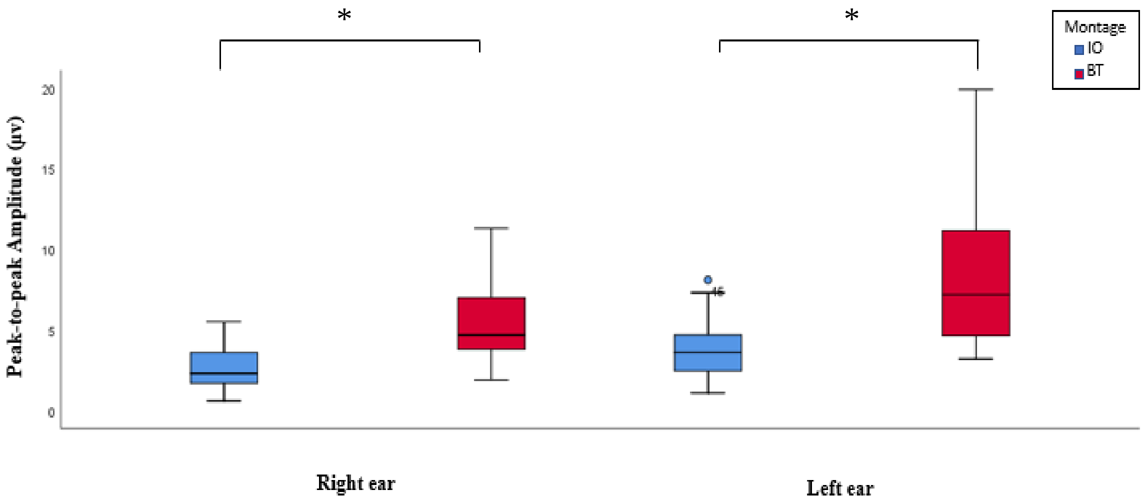
	Belly-tendon Montage				Infra-orbital Montage			
	Right ear		Left ear		Right ear		Left ear	
Parameter	N	Median (IQR)	N	Median (IQR)	N	Median (IQR)	N	Median (IQR)
Peak-to-peak Amplitude	42	4.80 (2.68)	40	8.35 (5.83)	29	2.50 (2.23)	27	4.00 (3.00)

Note. 'N': Number of ears with the presence of response out of 50 ears; 'IQR': interquartile range; the values within parentheses in the 'median' column are of interquartile range

Separate Wilcoxon-signed rank tests were performed to compare the peak-to-peak amplitude of oVEMP between the electrode montages in right and left ears. The results revealed a significantly higher peak-to-peak amplitude of oVEMPs from the BT montage than the IO montage in right ear [$Z = -4.623$, $p < 0.001$, $d = 0.86$], as well as left ear [$Z = -4.547$, $p < 0.001$, $d = 0.88$], with a large effect size. The BT montage showed a median increase of 92% and 108.75% in amplitude compared to the IO montage in right and left ears, respectively. Figure 4.4 shows the box plots of the peak-to-peak amplitude of oVEMP from the two electrode montages and the outcomes of comparison between them.

Figure 4.4

Boxplots of the Peak-to-peak Amplitude of Bone-Conduction Ocular Vestibular Evoked Myogenic Potentials from the Belly-tendon and Infra-orbital Electrode Montages, and the outcomes of Wilcoxon-signed Rank Test for Comparison Between Them



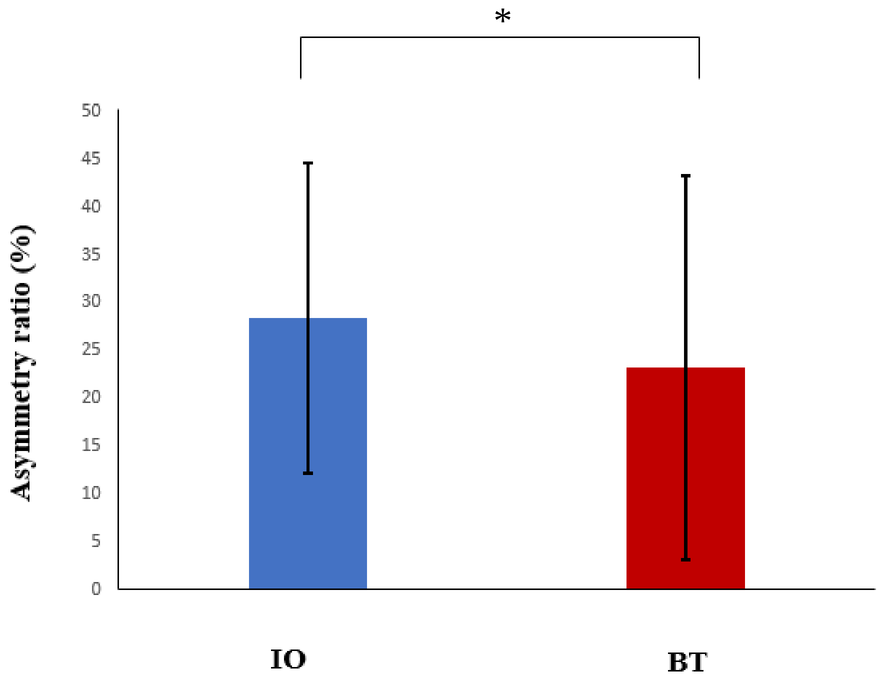
Note. 'BT': Belly-tendon; 'IO': Infra-orbital; * indicates a significant difference between the montages ($p < 0.05$, Wilcoxon-signed rank test)

4.1.4 Comparison of the inter-aural asymmetry ratio of BC-oVEMP between the BT and IO electrode montages.

The Shapiro-Wilk's test of normality revealed a normal distribution of the IAAR datasets of both the electrode montages ($p > 0.05$). Therefore, parametric statistical analysis was done. The mean IAAR of oVEMP from the BT montage was 23.12% (SD = 20.06), which was lower than that from the IO montage (Mean = 28.26%, SD = 16.20). A paired-samples t-test was performed to compare the IAAR of oVEMP between the electrode montages. Results indicated a significantly lower IAAR for oVEMP from the BT montage than IO montage [t (31) = 3.473, p = 0.002, *dz = 0.61]*, with a medium effect size. Figure 4.5 shows the bar graphs of IAAR of oVEMP from both electrode montages, and the outcomes of paired-samples t-test for comparison between them.

Figure 4.5

The Inter-aural Asymmetry Ratio of Bone-Conduction Ocular Vestibular Evoked Myogenic Potentials from the Belly-tendon and Infra-orbital Electrode Montages, and the Outcomes of Paired-samples t-test for Comparison Between Them



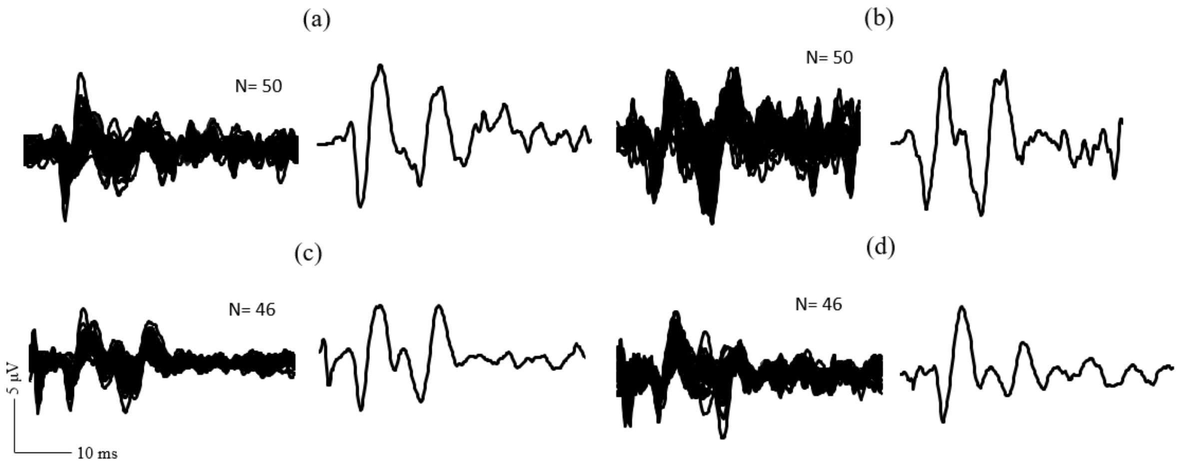
Note. ‘BT’: Belly-tendon electrode montage; ‘IO’: Infra-orbital montage; * indicates a significant difference between the montages ($p < 0.05$, Paired-samples t-test); the height of the bar represents the mean whereas the whisker shows standard deviation

4.2 Comparison of the response parameters of AC-oVEMP between BT and IO electrode montages

The contralateral oVEMPs in response to 500 Hz AC stimulation were recorded simultaneously from both ears of the individuals using the BT and IO electrode montages. Figure 4.6 shows the individual and grand-averaged oVEMP waveforms from both electrode montages.

Figure 4.6

The Individual and Grand-averaged Waveforms of the Air-Conduction Ocular Vestibular Evoked Myogenic Potentials Recorded using the Belly-tendon and Infra-orbital Electrode Montages



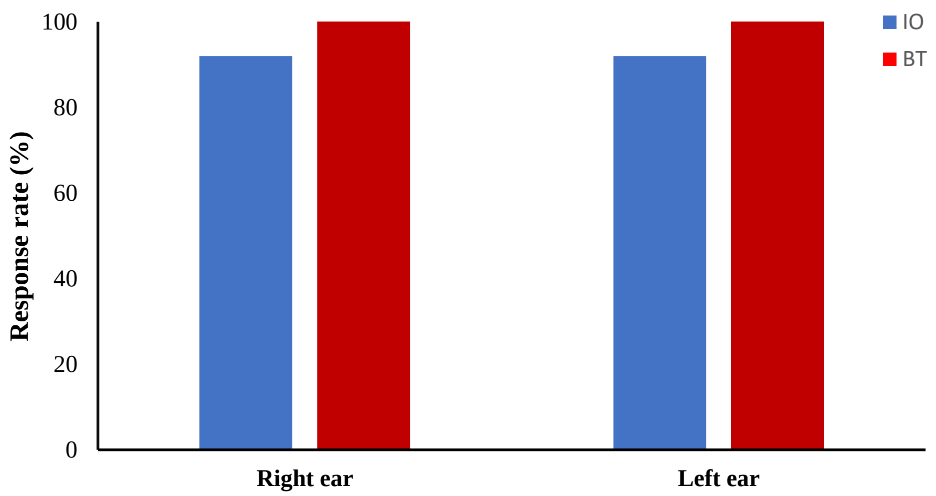
Note. (a) Responses from Belly-tendon electrode montage to right ear stimulation; (b) Responses from Belly-tendon electrode montage to left ear stimulation; (c) Responses from Infra-orbital electrode montage to right ear stimulation; (d) Responses from Infra-orbital electrode montage to right ear stimulation; ‘N’: number of ears with a present oVEMP out of 50 ears.

4.2.1 Comparison of the response rate of AC-oVEMP between the BT and IO electrode montages.

In response to the 500-Hz air-conduction stimulation, oVEMPs obtained using the BT montage were present in all the participants, resulting in a 100% response rate in both ears. However, oVEMPs obtained using the IO montage were absent in 4 right and 4 left ears, leading to the 92% response rate in each ear. The McNemar test revealed no significant difference in response rate between the electrode montages for air-conduction stimulation in both ears (p = 0.125). Figure 4.7 shows the comparison of the response rate of AC-oVEMP between the two electrode montages.

Figure 4.7

Response Rates of Air-Conduction Ocular Vestibular Evoked Myogenic Potentials from Infra-orbital and Belly-tendon Electrode Montages



Note. ‘BT’: Belly-tendon electrode montage; ‘IO’: Infra-orbital montage.

4.2.2 Comparison of the absolute latencies of AC-oVEMP between the BT and IO electrode montages.

The Shapiro-Wilk's test of normality revealed normal distribution of the absolute latencies of n1 and p1 peaks' datasets of both electrode montages ($p > 0.05$). Therefore, the descriptive statistical analyses were performed to obtain the mean and SD of the absolute latencies of oVEMP from both electrode montages. Table 4.3 shows the outcomes of the descriptive statistics.

Table 4.3

Mean and Standard Deviation of the Absolute Latencies of Individual Peaks (in ms) of Air-Conduction Ocular Vestibular Evoked Myogenic Potentials Recorded from the Belly-tendon and Infra-orbital Electrode Montages

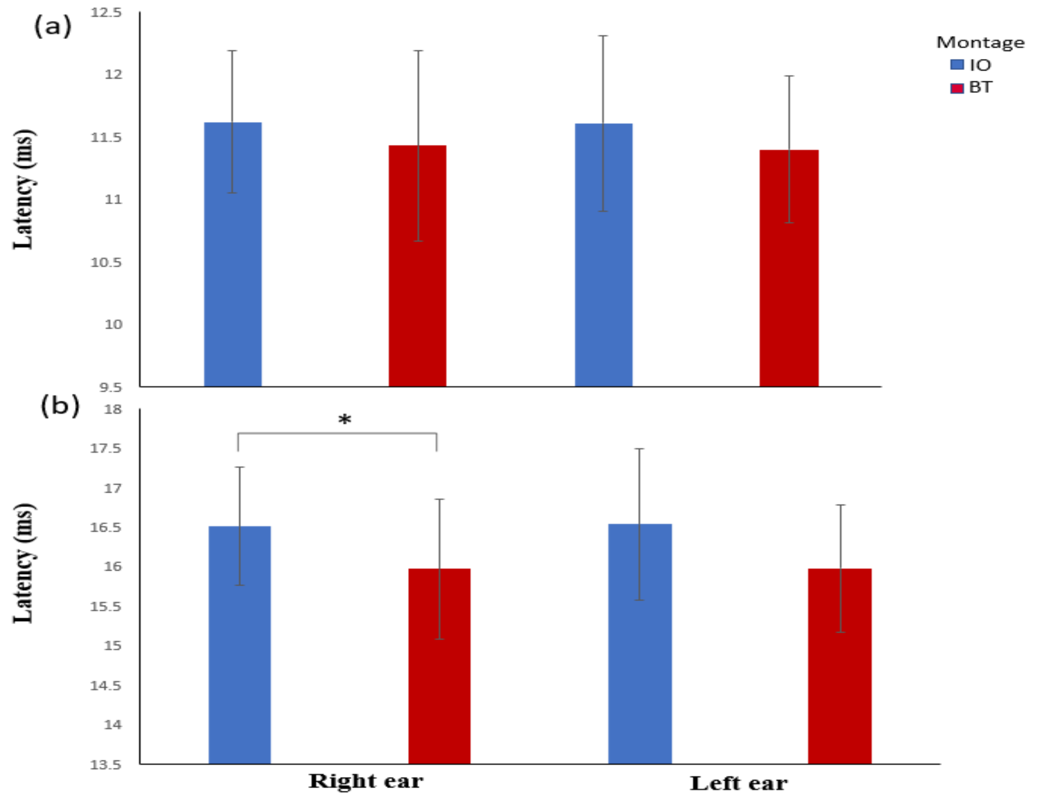
	Belly-tendon Montage				Infra-orbital Montage			
	Right ear		Left ear		Right ear		Left ear	
Parameter	N	M (SD)	N	M (SD)	N	M (SD)	N	M (SD)
n1 latency	50	11.43 (0.76)	50	11.40 (0.59)	46	11.62 (0.57)	46	11.61 (0.70)
p1 latency	50	15.97 (0.88)	50	15.98 (0.81)	46	16.51 (0.75)	46	16.54 (0.96)

Note. 'N': Number of ears with presence of response out of 50 ears; 'M': mean; 'SD': standard deviation; the values within parentheses in the 'mean' column are of standard deviation.

The results of the paired samples t-tests showed no significant difference in n1 latency between the electrode montages in right ear [t(45) = 1.505, p = 0.139] and left ear [t(45) = 1.858, p = 0.070]. There was also no significant difference in p1 latency of the left ear between the montages [t(45) = -0.797, p = 0.429]. On the contrary, the BT montage showed a significantly shorter p1 latency than the IO montage in right ear [t(45) = 2.280, p = 0.027, d_z = 0.34], with a small effect size. Figure 4.8 shows the bar graphs of n1 and p1 latencies of both electrode montages.

Figure 4.8

Absolute Latencies of n1 and p1 Peaks of Air-Conduction Ocular Vestibular Evoked Myogenic Potentials from the Belly-tendon and Infra-orbital Electrode Montages, and outcomes of Paired-samples t-test for Comparison Between Them



Note. (a) n1 latency (b) p1 latency; 'BT': Belly-tendon electrode montage; 'IO': Infra-orbital montage; * indicates a significant difference between the montages (p < 0.05, Paired-samples t-test); the height of the bar represents the mean whereas the whisker shows standard deviation

4.2.3 Comparison of the peak-to-peak amplitude of AC-oVEMP between the BT and IO electrode montages.

Following the finding of the violation of normality in the amplitude datasets ($p < 0.05$), descriptive statistical analyses were performed to obtain the median and interquartile range of the peak-to-peak amplitude of oVEMP from both electrode montages. Table 4.4 shows the outcomes of the descriptive statistics.

Table 4.4

Median and Interquartile Range of the Peak-to-peak Amplitude (in µV) of Air-Conduction Ocular Vestibular Evoked Myogenic Potentials Recorded from the Belly-tendon and Infra-orbital Electrode Montages

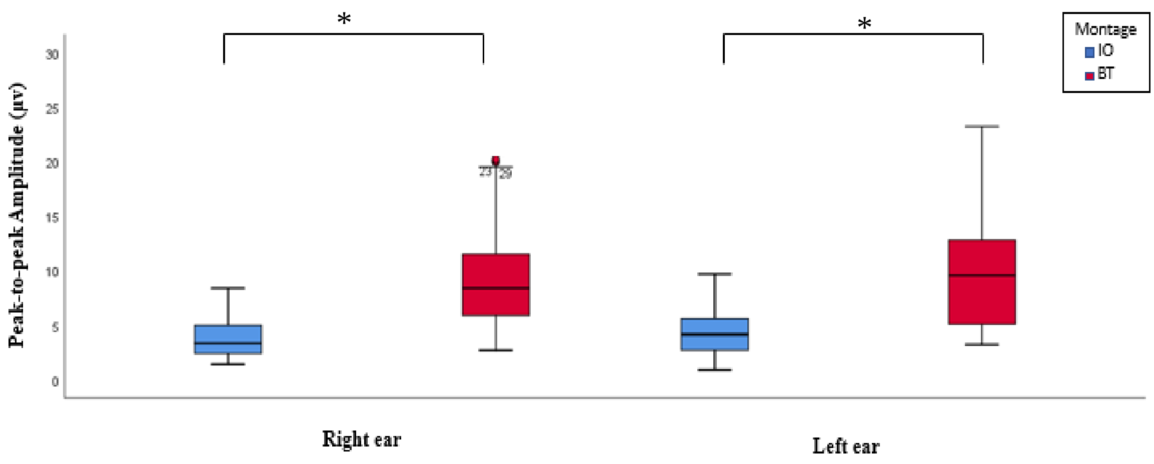
	Belly-tendon Montage				Infra-orbital Montage			
	Right ear		Left ear		Right ear		Left ear	
Parameter	N	Median (IQR)	N	Median (IQR)	N	Median (IQR)	N	Median (IQR)
Peak-to-peak Amplitude	50	9.10 (6.80)	50	10.20 (4.48)	46	4.10 (2.65)	46	4.95 (3.23)

Note. 'N': Number of ears with the presence of response out of 50 ears; 'IQR': interquartile range; the values within parentheses in the 'median' column are of interquartile range

The results of the Wilcoxon-signed rank test revealed a significantly higher peak-to-peak amplitude of oVEMP from the BT montage compared to the IO montage in right ear [Z = -5.905, $p < 0.001$, $d_z = 0.87$], as well as left ear [Z = -5.842, $p < 0.001$, $d_z = 0.86$], with a large effect size. The BT montage showed a median increase of 121.95% and 106.06% in amplitude compared to the IO montage in right and left ears, respectively. Figure 4.9 shows the box plots of the peak-to-peak amplitude of oVEMP obtained with the two electrode montages and the outcomes of comparison between them.

Figure 4.9

Boxplots of the Peak-to-peak Amplitude of Ocular Vestibular Evoked Myogenic Potentials from the Belly-tendon and Infra-orbital Electrode Montages, and the Outcomes of Wilcoxon-signed Rank Test for Comparison Between Them



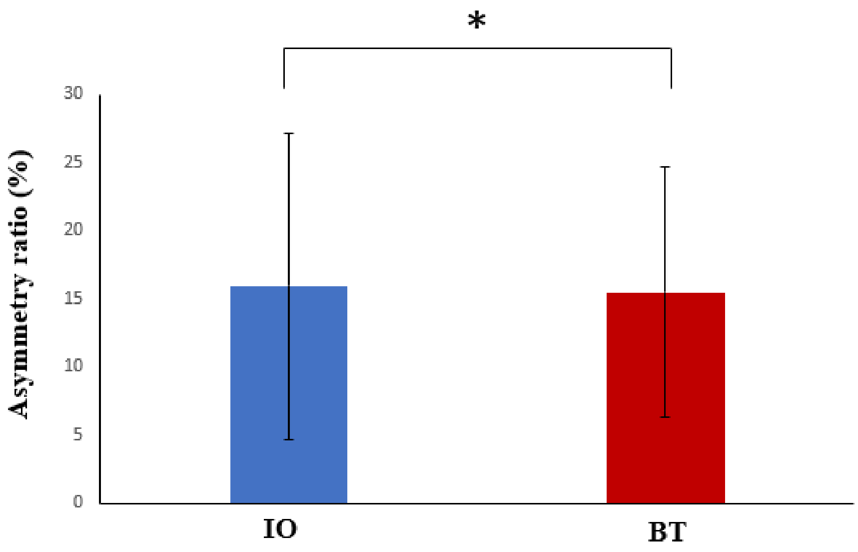
Note. 'BT': Belly-tendon electrode montage; 'IO': Infra-orbital montage; * indicates a significant difference between the montages ($p < 0.05$, Wilcoxon-signed rank test)

4.2.4 Comparison of the inter-aural asymmetry ratio of AC-oVEMP between the BT and IO electrode montages.

Following the finding of normal distribution of IAAR of oVEMP ($p > 0.05$), a paired-samples t-test was done to compare the IAAR of oVEMP between the electrode montages. Results showed a significantly higher IAAR of oVEMP when obtained using the IO montage ($M = 15.90$, $SD = 11.19$) than the BT montage ($M = 15.46$, $SD = 9.21$) [t (47) = 2.372, $p = 0.022$, dz = 0.35] with a small effect size. Figure 4.10 shows the bar graphs of IAAR of oVEMP from both electrode montages, and the outcome of paired-samples t-test for comparison between them.

Figure 4.10

The Inter-aural Asymmetry Ratio of Air-Conduction Ocular Vestibular Evoked Myogenic Potentials from the Belly-tendon and Infra-Orbital Electrode Montages, and the Outcomes of Paired-samples t-test for Comparison Between Them



Note. 'BT': Belly-tendon electrode montage; 'IO': Infra-orbital montage; * indicates a significant difference between the montages ($p < 0.05$, paired-samples t-test); the height of the bar represents the mean whereas the whisker shows standard deviation

4.3 Comparison of various response parameters of oVEMP between the stimulation modes when obtained using the IO electrode montage.

The response rates, absolute latencies of individual peaks, peak-to-peak amplitudes, and IAARs of oVEMP to 500-Hz tone bursts were compared between the stimulation modes.

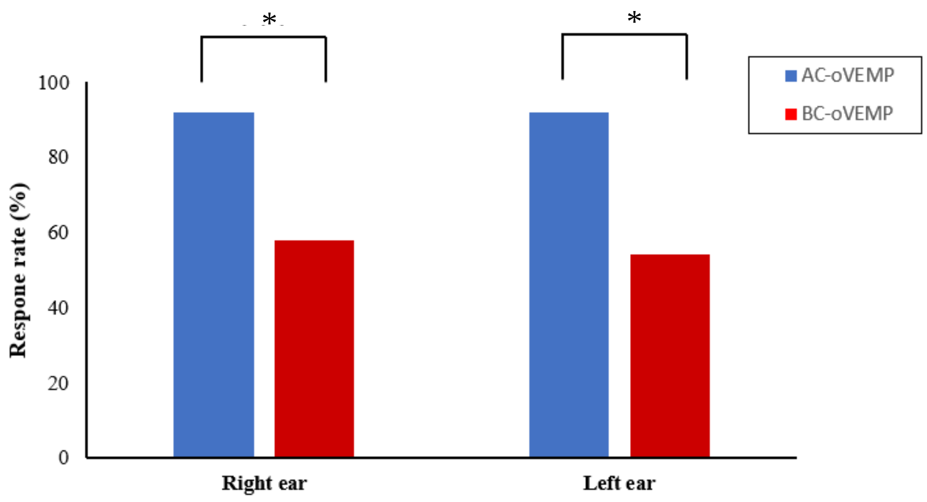
The outcomes of their comparison are delineated below under separate sub-headings for each response parameter.

4.3.1 Comparison of the response rates of oVEMP from the IO electrode montage between AC and BC modes of stimulation.

The BC-oVEMPs recorded from the IO electrode montage were absent in 21 right ears and 23 left ears, resulting in response rates of 58% and 54%, respectively. In contrast, AC-oVEMPs were absent in only 4 right ears and an equal number of left ears, resulting in a 92% response rate in each ear. The McNemar test revealed a significantly lower response rate of oVEMP to BC stimulation than to AC stimulation in both ears ($p < 0.001$). Figure 4.11 shows the response rates of AC- and BC-oVEMPs from the IO electrode montage, and the outcomes of McNemar test for the comparison between the modes.

Figure 4.11

Response Rates of Ocular Vestibular Evoked Myogenic Potentials to Air-conduction and Bone-conduction Stimulations for Responses from the Infra-orbital Electrode Montage, and the outcomes of McNemar Test for Comparison Between the Modes



Note. ‘AC’: air-conduction; ‘BC’: bone-conduction; ‘oVEMP’: ocular vestibular evoked myogenic potential; * indicates a significant difference between the stimulation modes ($p <$ 0.05, McNemar test).

4.3.2 Comparison between the stimulation modes on the absolute latencies of oVEMP obtained using the IO electrode montage.

The absolute latencies of oVEMPs obtained using the IO montage were normally distributed for both stimulation modes ($p > 0.05$). Therefore, the descriptive statistical analyses were performed to obtain the mean and SD of the absolute latencies. Table 4.5 shows the outcomes of the descriptive statistics.

Table 4.5

Mean and Standard Deviation of the Absolute Latencies of Individual Peaks (in ms) of Ocular Vestibular Evoked Myogenic Potentials Recorded from the Infra-orbital Electrode Montages using Air-Conduction and Bone-Conduction Stimulation

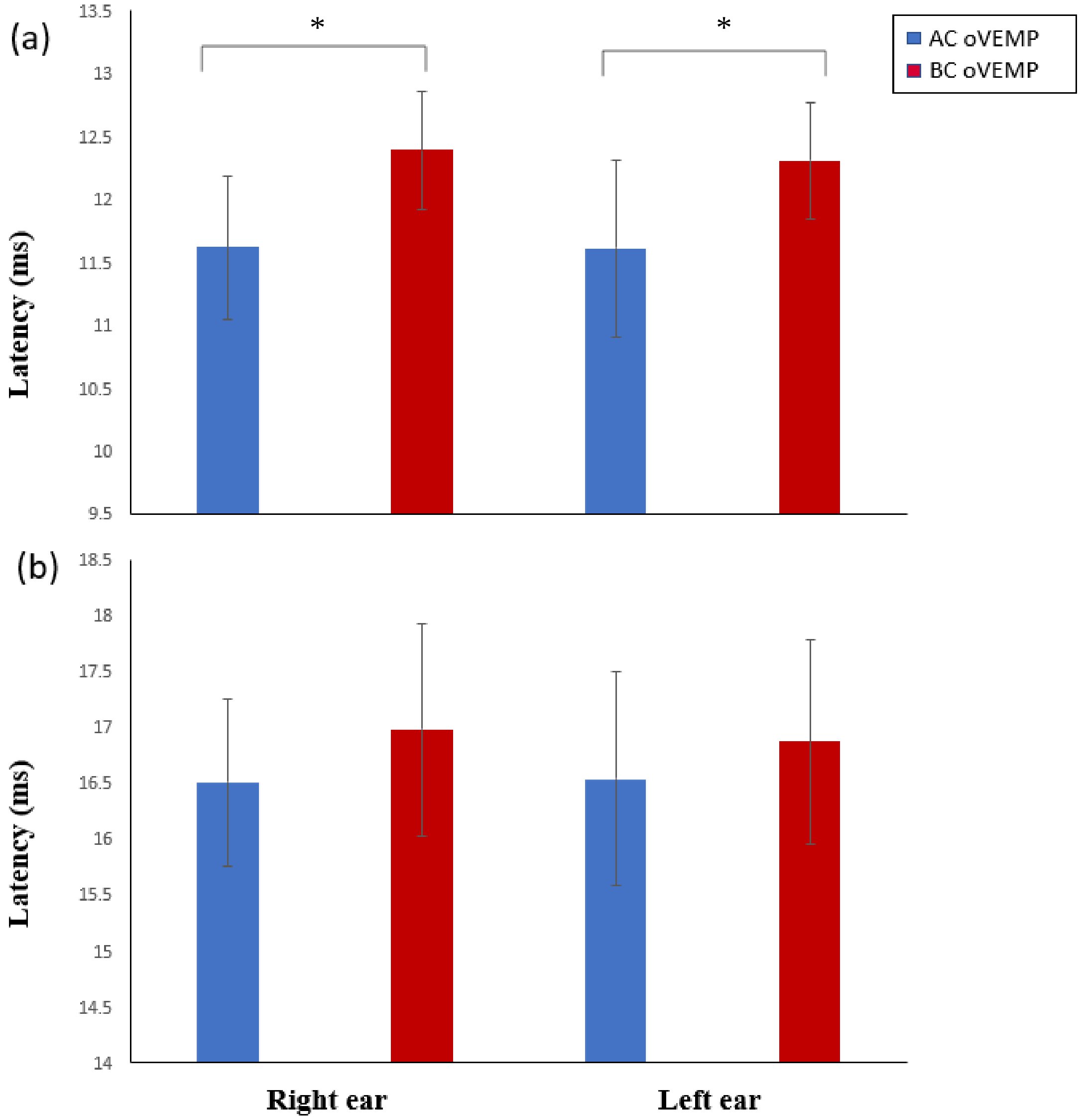
	Air-Conduction				Bone-Conduction			
	Right ear		Left ear		Right ear		Left ear	
Parameter	N	M (SD)	N	M (SD)	N	M (SD)	N	M (SD)
n1 latency	46	11.62 (0.57)	46	11.61 (0.70)	21	12.39 (0.47)	27	12.31 (0.46)
p1 latency	46	16.51 (0.75)	46	16.54 (0.96)	21	16.98 (0.95)	27	16.87 (0.91)

Note. 'N': Number of ears with the presence of response out of 50 ears; 'M': mean; 'SD': standard deviation; the values within parentheses in the 'mean' column are of standard deviation.

The results of paired samples t-tests showed a significant difference in n1 latency between the stimulation modes in right ear [$t(25) = -5.652$, $p < 0.001$, $d_z = 1.23$] and left ear [$t(23) = -2.897$, $p = 0.008$, $d_z = 0.56$], with a medium to large effect size. However, there was no significant difference in p1 latency between the stimulation modes for the right ear [$t(25) = -1.625$, $p = 0.117$] and the left ear [$t(23) = -0.327$, $p = 0.747$]. Figure 4.12 shows bar graphs of n1 and p1 latencies and the outcomes of comparison between the stimulation modes.

Figure 4.12

Absolute Latencies of n1 and p1 Peaks of Ocular Vestibular Evoked Myogenic Potentials from the Infra-orbital Electrode Montage using Air-Conduction and Bone-Conduction Stimulation, and the Outcomes of Comparison between the Stimulus Modes



Note. (a) n1 latency (b) p1 latency; ‘AC’: air-conduction; ‘BC’: bone-conduction; ‘oVEMP’: ocular vestibular evoked myogenic potential; * indicates statistical significant difference ($p < 0.05$, paired-samples t-test); the height of the bar represents the mean whereas the whisker shows standard deviation.

4.3.3 Comparison between the stimulation modes on the peak-to-peak amplitude of oVEMP from the IO electrode montage.

Following the finding of the violation of normality in the amplitude datasets ($p < 0.05$), descriptive statistical analyses were performed to obtain the median and IQR of the peak-to-peak amplitude of oVEMP obtained with air-conduction and bone-conduction stimulation modes. Table 4.6 shows the outcomes of the descriptive statistics.

Table 4.6

Median and Interquartile Range of the Peak-to-peak Amplitude (in µV) of Air-conduction and Bone-conduction Ocular Vestibular Evoked Myogenic Potentials Recorded from the Infra-orbital Electrode Montage

	Air-Conduction				Bone-Conduction			
	Right ear		Left ear		Right ear		Left ear	
Parameter	N	Median (IQR)	N	Median (IQR)	N	Median (IQR)	N	Median (IQR)
Peak-to-peak Amplitude	46	4.10 (2.65)	46	4.95 (3.23)	21	2.50 (2.23)	27	4.00 (3.00)

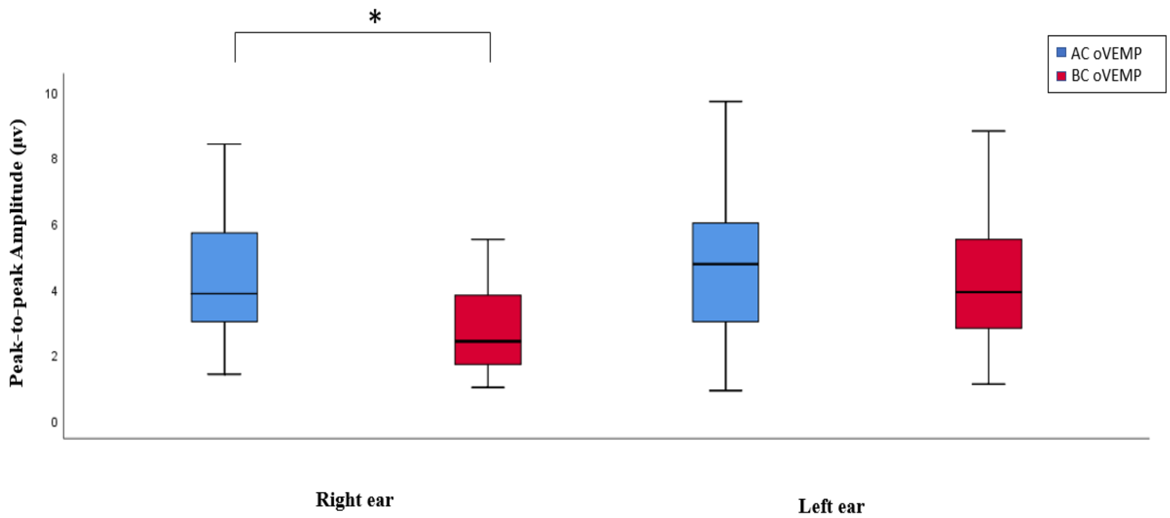
Note. 'N': Number of ears with the presence of response out of 50 ears; 'IQR': interquartile range; the values within parentheses in the 'median' column are of interquartile range.

The Wilcoxon-signed rank test revealed a significant difference in peak-to-peak amplitude between the stimulation modes in right ear [$Z = -2.571$, $p = 0.010$, $dz = 0.56$] with a medium effect size. On the contrary, there was no significant difference in peak-to-peak amplitude between the stimulation modes in the left ear [$Z = -1.057$, $p = 0.290$]. Figure 4.13

shows box plots of the peak-to-peak amplitude of oVEMP obtained with both stimulation modes.

Figure 4.13

Boxplots of the Peak-to-peak Amplitude of Ocular Vestibular Evoked Myogenic Potentials from the Infra-orbital Electrode Montage in response to Air-Conduction and Bone-Conduction Modes of Stimulation, and the Outcomes of Wilcoxon Signed-rank Test for Comparison Between Them



Note. ‘AC’: air-conduction; ‘BC’: bone-conduction; ‘oVEMP’: ocular vestibular evoked myogenic potential; * indicates a significant difference between the stimulation modes ($p <$ 0.05, Wilcoxon-signed rank test).

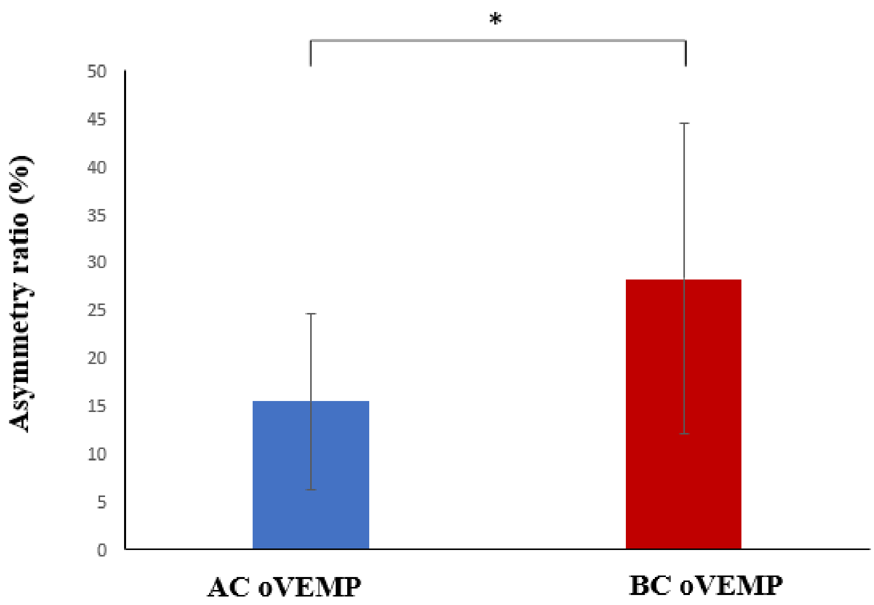
4.3.4 Comparison between the stimulation modes on the inter-aural asymmetry ratio of oVEMP obtained using the IO electrode montage.

Following the finding of normal distribution of IAAR of oVEMP elicited using the AC and BC stimulation modes from the IO electrode montage (p > 0.05), parametric statistical analyses were subsequently performed. The mean IAAR for BC mode was 28.26%

(SD = 16.20), which was higher than the AC mode (Mean = 15.46%, SD = 9.25). The results of statistical comparison using paired-samples t-test showed significantly higher IAAR for oVEMP from the BC stimulation than the AC stimulation [t (30) = -2.608, p = 0.014, d = 0.47], with a small effect size. Figure 4.14 shows the bar graphs of IAAR of oVEMP from both modes of stimulation.

Figure 4.14

Inter-aural Asymmetry Ratio of Ocular Vestibular Evoked Myogenic Potentials from the Infra-orbital Electrode Montage in Response to Air-conduction and Bone-conduction Stimulations and the outcomes of Paired-samples t-test for Comparison Between Them



Note. ‘AC’: air-conduction; ‘BC’: bone-conduction; ‘oVEMP’: ocular vestibular evoked myogenic potential; * indicates a significant difference between the stimulation modes (*p* < 0.05, paired-samples t-test); the height of the bar represents the mean whereas the whisker shows standard deviation

4.4 Comparison of various response parameters of oVEMP between the stimulation modes when obtained using the BT electrode montage

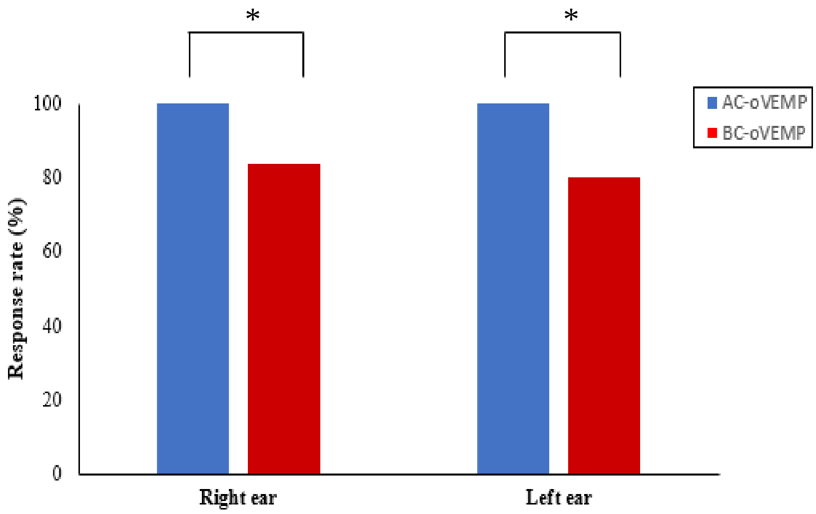
The response rates, absolute latencies of individual peaks, peak-to-peak amplitudes, and IAARs of oVEMP to 500-Hz tone bursts were compared between the stimulation modes. The outcome of their comparison are delineated below under separate sub-headings for each response parameter.

4.4.1 Comparison of the response rates of oVEMP from the BT electrode montage between AC and BC modes of stimulation.

The oVEMP responses from the BT electrode montage, elicited with AC stimulation, revealed a 100% response rate in both the right and left ears. In contrast, when elicited using a BC stimulation, the oVEMP responses were present only in 84% and 80% of right and left ears, respectively. On the statistical comparison, the McNemar test revealed a significantly lower response rate of oVEMP to BC stimulation than in AC stimulation in both ears ($p < 0.01$). Figure 4.15 shows the response rates of AC- and BC-oVEMPs from the BT electrode montage, and the outcomes of McNemar test for the comparison between the modes.

Figure 4.15

Response Rates of Air-conduction and Bone-conduction Ocular Vestibular Evoked Myogenic Potentials from the Belly-tendon Electrode Montage, and the outcomes of McNemar test for Comparison Between the Modes



Note. ‘AC’: air-conduction; ‘BC’: bone-conduction; ‘oVEMP’: ocular vestibular evoked myogenic potential; * indicates a significant difference between the stimulation modes ($p < 0.05$, McNemar test).

4.4.2 Comparison between the stimulation mode on the absolute latencies of oVEMP obtained using the BT electrode montage.

The absolute latency datasets of oVEMPs obtained using the BT montage were normally distributed for both stimulation modes ($p > 0.05$). Therefore, the descriptive statistical analyses were performed to obtain the mean and SD of the absolute latencies. Table 4.7 shows the outcomes of the descriptive statistics.

Table 4.7

Mean and Standard Deviation of the Absolute Latencies of Individual Peaks (in ms) of Ocular Vestibular Evoked Myogenic Potentials Recorded from the Belly-tendon Electrode Montages using Air-Conduction and Bone-Conduction Stimulation

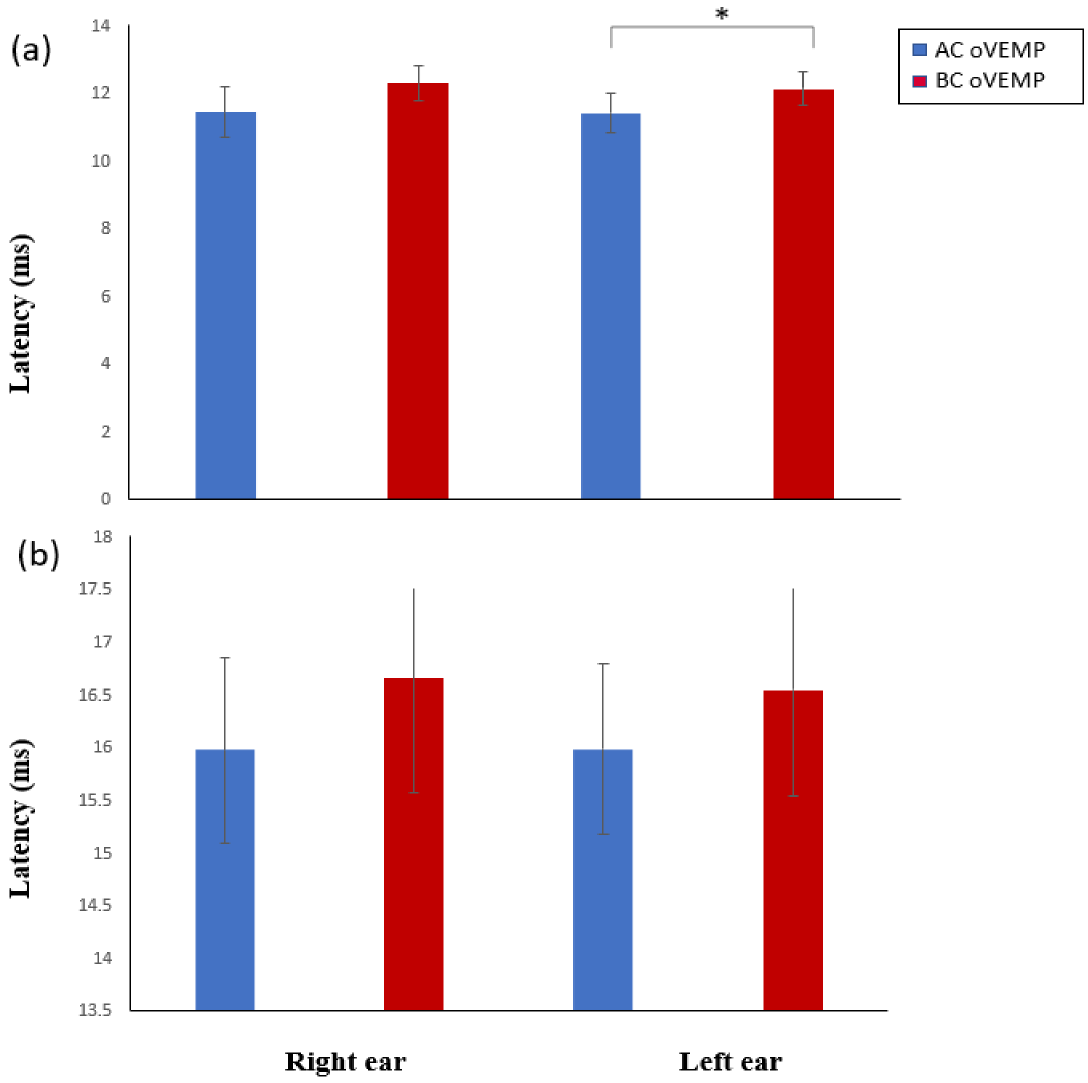
	Air-Conduction				Bone-Conduction			
	Right ear		Left ear		Right ear		Left ear	
Parameter	N	M (SD)	N	M (SD)	N	M (SD)	N	M (SD)
n1 latency	50	11.43 (0.76)	50	11.40 (0.59)	42	12.28 (0.53)	40	12.12 (0.49)
p1 latency	50	15.97 (0.88)	50	15.98 (0.81)	42	16.65 (1.09)	40	16.54 (1.00)

Note. 'N': Number of ears with the presence of response out of 50 ears; 'M': mean; 'SD': standard deviation; the values within parentheses in the 'mean' column are of standard deviation.

The results of the paired samples t-tests showed no significant difference in n1 latency between the stimulation modes in right ear [t(41) = -1.751, p = 0.087], as well as for the p1 latency in the right ear [t(41) = -0.876, p = 0.386] and left ear [t(34) = 0.978, p = 0.334]. However, the n1 latency revealed a significant difference between the stimulation modes in left ear [t(39) = -2.654, p = 0.011, dz = 0.27], with a small effect size. Figure 4.16 shows the bar graphs of n1 and p1 latencies and the outcomes of comparison between the stimulation modes.

Figure 4.16

Absolute Latencies of n1 and p1 Peaks of Ocular Vestibular Evoked Myogenic Potentials from the Belly-tendon Electrode Montage using Air-Conduction and Bone-Conduction Stimulation, and the Outcomes of Comparison Between the Stimulation Modes



Note. (a) n1 latency (b) p1 latency; ‘AC’: air-conduction; ‘BC’: bone-conduction; ‘oVEMP’: ocular vestibular evoked myogenic potential; * indicates a significant difference between the stimulation modes ($p < 0.05$, paired-samples t-test); the height of the bar represents the mean whereas the whisker shows standard deviation

4.4.3 Comparison between the stimulation modes on the peak-to-peak amplitude of oVEMP from the BT electrode montage.

Following the finding of normality violation in the amplitude datasets ($p < 0.05$), descriptive statistical analyses were performed to obtain the median and IQR of the peak-to-peak amplitude of oVEMP obtained with air-conduction and bone-conduction stimulation modes. Table 4.8 shows the outcomes of the descriptive statistics.

Table 4.8

Median and Interquartile Range of the Peak-to-peak Amplitude (in µV) of Air-conduction and Bone-conduction Ocular Vestibular Evoked Myogenic Potentials Recorded from the Belly-tendon Electrode Montage

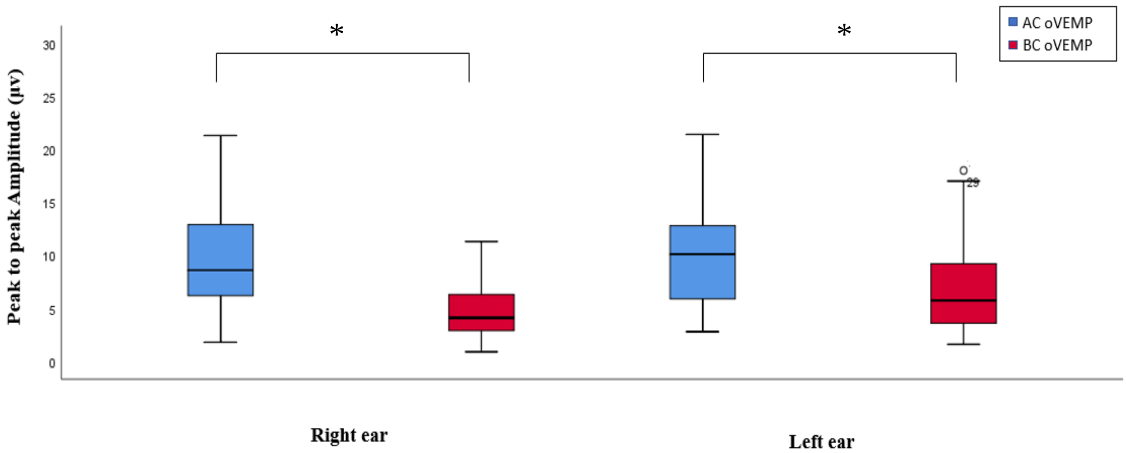
	Air-conduction				Bone-conduction			
	Right ear		Left ear		Right ear		Left ear	
Parameter	N	Median (IQR)	N	Median (IQR)	N	Median (IQR)	N	Median (IQR)
Peak-to-peak Amplitude	50	9.1 (6.80)	50	10.20 (4.48)	42	4.80 (2.68)	40	8.35 (5.83)

Note. 'N': Number of ears with presence of response out of 50 ears; 'IQR': interquartile range; the values within parentheses in the 'median' column are of interquartile range.

The results of the Wilcoxon-signed rank test revealed a significant difference in peak-to-peak amplitude between the stimulation modes in right ear [Z = -4.387, $p < 0.001$, dz = 0.45] and left ear [Z = 3.175, p = 0.001, dz = 0.33], with a small to medium effect size. Figure 4.17 shows box plots of the peak-to-peak amplitude of oVEMP obtained with both stimulation modes.

Figure 4.17

Boxplots of the Peak-to-peak Amplitude of Ocular Vestibular Evoked Myogenic Potentials from the Belly-tendon Electrode Montage in Response to Air-conduction and Bone-conduction Modes of Stimulations, and the Outcomes of Wilcoxon-signed Rank Test for Comparison Between Them



Note. ‘AC’: air-conduction; ‘BC’: bone-conduction; ‘oVEMP’: ocular vestibular evoked myogenic potential; * indicates a significant difference between the stimulation modes (p < 0.05, Wilcoxon signed-rank test).

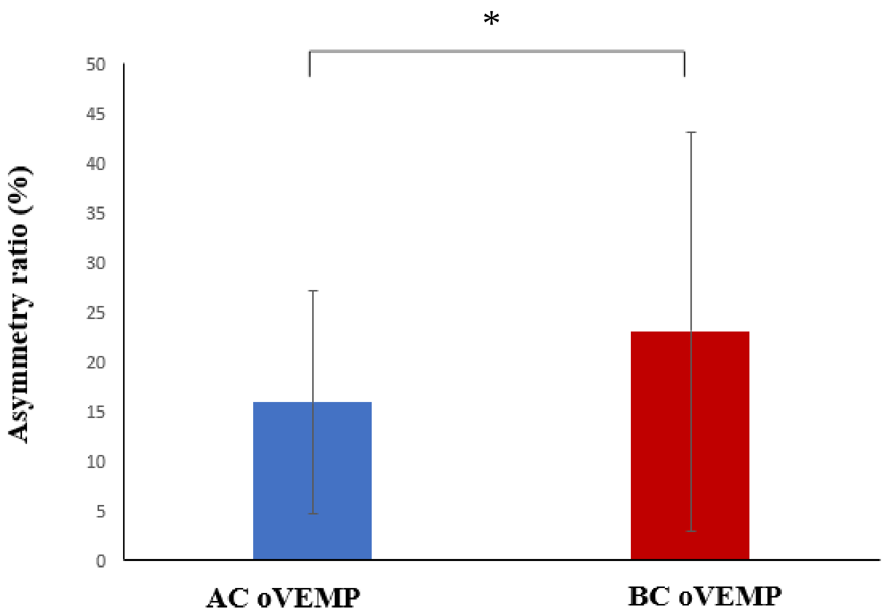
4.4.4 Comparison between the stimulus modes on the inter-aural asymmetry ratio oVEMP obtained using the BT electrode montage.

Following the finding of normal distribution of IAAR of oVEMP elicited using the AC and BC stimulation modes from the BT electrode montage (p > 0.05), parametric statistical analyses were subsequently performed. The mean IAAR for BC mode was 23.12% (SD = 20.06), which was higher than the AC mode (Mean = 15.90%, SD = 11.19). The results of statistical comparison using paired-samples t-test showed significantly higher IAAR for oVEMP from the BC stimulation than the AC stimulation [t (41)= -2.769, p =

0.008, d = 0.43], with a small effect size. Figure 4.18 shows the bar graph of IAAR of oVEMP from both modes of stimulation.

Figure 4.18

Inter-aural Asymmetry Ratio of Ocular Vestibular Evoked Myogenic Potentials from the Belly- tendon Electrode Montage in Response to Air-conduction and Bone-conduction Stimulations and the Outcomes of Paired-samples t-test for Comparison Between Them



Note. ‘AC’: air-conduction; ‘BC’: bone-conduction; ‘oVEMP’: ocular vestibular evoked myogenic potential; * indicates a significant difference between the stimulation modes ($p <$ 0.05, paired-samples t-test); the height of the bar represents the mean whereas the whisker shows standard deviation

Chapter V

Discussion

The present study investigated the effect of two different electrode montages, Belly-tendon (BT) and Infra-orbital (IO), on Ocular vestibular evoked myogenic potential (oVEMP) when elicited using air-conduction (AC) and bone-conduction (BC) vibration in 50 healthy adults. The findings yielded several observations pertaining to response rate, absolute latencies of n1 and p1 peaks, peak-to-peak amplitude, and inter-aural asymmetry ratio (IAAR). These parameters were compared between the electrode montages and stimulation modes to understand the difference caused by electrode montages and stimulation modes on the response parameters of oVEMP.

5.1 Comparison of the response parameters of BC-oVEMP between BT and IO electrode montages

5.1.1 Response Rate of BC-oVEMP

In the present study, the response rate of BC-oVEMP from the BT montage was significantly higher than from the IO montage. The previous studies comparing these two montages revealed similar trend of higher response rate with BT montage than with the IO montage; however, they either did not carry out statistical comparisons (Vanspauwen et al., 2017 and Heijdt, 2017), or the difference did not reach statistical significance levels (Ansari, 2025). On statistical comparison, using the data from Vanspauwen et al (2017) and Heijdt (2017), the difference in response rate between IO and BT montages was not significantly different ($p > 0.05$).

The reason for the dissonance with the findings of the studies by Vanspauwen et al. (2017) and Heijdt (2017) could be the differences in the transducer and the inherent change in the stimulus characteristics that come with it. These studies used minishaker as opposed to the Radioear B71 bone vibrator used in the present study. The differences in findings from the study by Ansari (2025) could be the stimulus characteristics. Ansari (2025) used a rise-plateau-fall time of 0-4-0 ms, whereas the present study used 2-2-2 cycles, amounting to 4-4-4 ms of rise-plateau-fall time. These methodological differences may explain why the BT advantage reached significance in the present study but was not in the above studies.

The reason for the BT montage showing optimal response rates in our study could be attributed to the anatomy of the muscle and electrode placement. In BT montage, both electrodes (active and reference) are placed on the IOM, aligning with the inferior oblique muscle fibre orientation, maximising capture of motor unit activity travelling along the muscle fibres. This also reduces energy dissipation by volume conduction due to the electrodes being placed on the belly of the muscle. However, in the IO montage, the active electrode is placed over IOM, but the reference electrode is placed 2 cm below, which is nearly perpendicular to current flow, reducing the chance of picking up a robust IOM potential (Raveendran & Singh, 2026). The variation in electrode placement on the IOM might result in differences in response rate across the montages.

5.1.2 Absolute Latencies of BC-oVEMP

The present study found a trend towards shorter absolute latencies of n1 and p1 peaks of BC-oVEMP from the BT montage than the IO montage; however, this difference between the montages was statistically not significant. These findings are in agreement with Ansari (2025), who also reported no significant difference in latencies between the two montages for BC-oVEMP. A pattern of shorter n1 and p1 latencies with BT montage was observed in another study, but it was statistically significant only for p1 latencies in right ear (Vanspauwen et al., 2017).

In the BT montage, both electrodes are placed along the inferior oblique muscle, allowing better and faster recording of the muscle response, whereas in the IO montage, the reference electrode is placed away from the muscle, causing the electrical potential to travel through other tissues and resulting in longer latencies for IO montage (Raveendran & Singh, 2026). Though the present study found a similar trend, the difference found was not significant due to possible individual variability in latencies among study participants, probably suggesting that a larger sample size might paint a clearer picture.

5.1.3 Peak-to-Peak Amplitude of BC-oVEMP

The peak-to-peak amplitude of BC-oVEMP from the BT montage was significantly higher than the IO montage, with a large effect size. The mean peak-to-peak amplitude of BT montage had amplitudes approximately 2.14 times and 2.20 times greater than the IO montage for right and left ears, respectively. These findings report the advantage of BT montage, which is consistently observed with other published results that demonstrate that BT montage produces larger and more robust oVEMP responses than the IO montage for BC-oVEMP (Vanspauwen et al., 2017; Heijdt, 2017). However, these findings are conflicting with another study on BC-oVEMP by Ansari (2025) who reported no significant difference in amplitude between the IO and BT montages. As mentioned in the previous section on BC-oVEMP response rate, the differences in the stimulus characteristics could lead to differences. Thus, the above studies suggests that there is influence of stimulus duration on the amplitude of oVEMP. So, it is plausible that the differences in these stimulus durations could have led to the differences in the findings between the studies.

As explained in the section of response rate of BC-oVEMP, the BT montage’s active and reference electrodes are placed on the belly and tendon of the IOM, respectively, which ensures an optimal differential recording across the muscle's most electrically active regions. In the case of IO montage the reference electrode is placed at a point 2 cm directly below the active electrode, causing it to lie in a region away from the IOM.

An explanation for the amplitude advantage of BT montage over the IO montage was given by Piker et al. (2018). The placement of reference electrode in the BT montage is on the medial canthus which records a phase-inverted signal, and differential amplification results in addition of signal components from both active and reference electrodes, thus producing an augmented output. In contrast, in the IO montage, both electrodes lie in close proximity within the same electrical field generated by the IOM. Hence both the electrodes record the same phase signal which leads to signal subtraction during differential amplification, causing the signal amplitude to reduce in IO montage. Thus, the present study confirms that the amplitude advantage of the BT montage is preserved under BC stimulation, reinforcing its clinical utility. Also, the large effect sizes observed in the present study indicate that the superiority of the BT montage is not only statistically significant but also clinically meaningful and generalizable.

5.1.4 Inter-Aural Asymmetry Ratio of BC-oVEMP

The present study found that the IAAR for BC-oVEMP was significantly lower in the BT montage compared to the IO montage, with a medium effect size. Lower asymmetry in BT montage as compared to IO montage has also been noted by Vanspauwen et al. (2017). Lower asymmetry ratios generally indicate better symmetry between ears and greater recording stability, which is expected in healthy individuals (Iwasaki et al., 2007; Brix et al., 2019). The BT montage records more consistent muscle activity, reducing inter-subject and inter-ear variability, whereas in the IO montage, the reference electrode placement away from the muscle makes the signal more susceptible to volume-conducted noise that can vary between sides. Hence, lower asymmetry in the BT montage indicates better symmetry between the ears. This could be attributed to the placement of active electrode and reference electrode on the IOM in BT montage.

5.2 Comparison between BT and IO electrode montages for AC-oVEMP

5.2.1 Response Rate of AC-oVEMP

The response rate for AC-oVEMP was 100% with the BT montage, which was higher than the 92% with the IO montage for both ears, although the difference was not statistically different. The trend of higher response rate with the BT montage is consistent with several previous studies (Raveendran & Singh, 2024, 2026; Mat et al., 2023). As mentioned in the section on the response rate of BC-oVEMP, the reasons for electrode placement yielding a higher response rate with the BT montage also apply to AC stimulation. As electrode placement determines the efficiency of recording the IOM's electrical activity, this anatomical rationale applies equally across stimulation modes.

5.2.2 Absolute Latencies of AC-oVEMP

The absolute latencies of AC-oVEMP showed variable results across the montages. The n1 latencies showed statistically no significant difference between the BT and IO montages for both ears. Further, in right ear the p1 latency was significantly shorter for AC-oVEMPs from the BT montage than the IO montage. While the p1 latencies were shorter for the BT montage than the IO montage for left ear too, the difference did not reach statistically significant proportions. In fact, this trend was true even for n1 latency. Similar observations have been consistently reported in earlier literature, suggesting that electrode placement has influence on latency measures as previously mentioned (Raveendran & Singh, 2026).

5.2.3 Peak-to-Peak Amplitude of AC-oVEMP

In the present study, the BT montage showed significantly larger peak-to-peak amplitude than the IO montage for AC-oVEMP in both the ears. The BT montage had 2.27 times greater amplitude than the IO montage. This finding is in strong agreement with multiple earlier studies that consistently identified that BT montage is superior in terms of amplitude enhancement. In comparison to the IO montage, Sandhu et al. (2013), Makowiec et al. (2019), and Raveendran and Singh (2024) all reported significantly larger amplitudes and improved signal quality using the BT montage. The increased amplitudes with BT montage are likely related to more effective recording of inferior oblique muscle activity which could be explained by the positioning of the electrodes. The placement of active electrode in BT montage is below the lateral canthus, aligning more closely with the motor zone of the IOM whereas the active electrode in the IO montage is placed in the infra-orbital midline (Sandhu et al., 2013; Raveendran & Singh, 2024). The spatial orientation of the belly of the muscle and the placement of active electrode on it enables more direct capture of the electromyographic activity generated by the IO muscle, resulting in a stronger, more detectable response in the BT montage. Hence, BT montage has consistently shown improved signal amplitude when compared to IO montage (Raveendran & Singh, 2024). As mentioned in the previous section, the larger amplitudes observed with the BT montage may also be attributed to the enhanced differential voltage gradient and summation of phase-inverted signals recorded from the active and reference electrodes, whereas the IO montage is more susceptible to signal cancellation due to both electrodes recording signals of similar polarity (Piker et al., 2018; Raveendran & Singh, 2024).

5.2.4 Inter-Aural Asymmetry Ratio of AC-oVEMP

The present study found a significant difference in IAAR between the BT and IO montages for AC-oVEMP with a small effect size. The IAAR with the IO montage was found to be relatively higher than with the BT montage. Similar differences in inter-aural amplitude asymmetry ratios across montages, with asymmetry ratios being lower with the BT montage than with the IO montage, have been reported previously (Mat et al., 2023 and Leyssens et al., 2017), although the differences between the montages did not reach statistically significant proportion in these studies. The absence of statistical significance may be attributed to the limited sample size in these studies and could also be attributed to minor differences in electrode placement and appropriate muscle activation with gaze elevation.

5.3 Comparison of response parameters between AC-oVEMP and BC-oVEMP using IO montage

5.3.1 Response Rate

The present study observed higher response rates for AC-oVEMP when compared to BC-oVEMP when using the IO montage. While AC stimulation yielded response rates of 92% bilaterally, the response rate with BC stimulation were 58% in right ear and 54% in left ear. The lower response rate observed for BC-oVEMP compared to AC-oVEMP is consistent with the findings of Rosengren et al. (2011). They reported an AC-oVEMP's response rate of 81% as opposed to 62% for BC-oVEMPs. In contrast, Fröhlich et al. (2021) reported better response rates (83–92%) for BC-oVEMP than AC-oVEMP (78–87%). They had used B81 transducer for BC stimulation and reported that the tranducer type may have played a role in better response rate for BC-oVEMP. This could be attributed to the higher output capability and better vibratory transmission efficiency of B81 transducer as compared to the B71 transducer that was used in the present study. Therefore, the transducer type may have played a role in the differences in response rate in the two studies. The difference in response rate between the modes may be due to the bone-conducted vibration which depends on mechanical transmission through the skull bones, and this transmission can vary between individuals depending on skull properties (thickness), placement of the vibrator, and direction of vibration.

5.3.2 Absolute Latencies

The present study showed a significant difference in n1 latency between the stimulation modes for both the right and left ears, whereas no significant difference was observed for p1 latency even though trend for p1 latency was similar to the n1 latency. The n1 latencies were significantly longer in BC-oVEMP than AC-oVEMP. The prolonged n1 latency observed for BC-oVEMP may be related to variability in the BC stimulation mode, producing less synchronous activation. Longer latencies of BC mode could be due to the differential optimal stimulus duration for BC-oVEMP than AC-oVEMP. The optimal BC-oVEMP duration of 2-4 ms produces best oVEMPs and deteriorates with the increase in stimulus duration beyond 4ms (Lim et al., 2013). However, such detrimental effects are less obvious for AC-oVEMPs. Since the BC-oVEMPs were generated using a 12-ms tone burst, it might have led to response adaptation leading to longer latencies.

5.3.3 Peak-to-Peak Amplitude

The amplitude of AC-oVEMP in the present study were higher than that of BC-oVEMP for IO montage. This is contrary to some studies that have reported larger BC-oVEMP amplitudes than AC-oVEMP amplitudes (Fröhlich et al., 2021). Fröhlich et al. (2021) found that amplitudes were higher for BCV (bone-conducted vibration) than ACS (air-conducted sound) in their 24 healthy normal subjects using the B81 transducer. Moreover, the author's placement of the bone-conduction device was on the forehead, and the current study used mastoid stimulation. The discrepancy may be related to the placement of bone vibrator or the specific transducer (B71) used in the present study. Patterson et al. (2021) study found that for oVEMPs, the impulse hammer (IH) stimulus had significantly higher amplitudes than both B81 and ACS. Further, Greenwalt et al. (2021) compared minishaker and B71 bone vibrator and reported robust responses with minishaker. They also reported poor test-retest reliability in adults using B71 bone vibrator. These findings collectively suggest that BC stimulation is more susceptible to the type of transducer and transducer placement than AC stimulation. Furthermore, a large duration tone burst (12 ms) in the present study might have differently affected the AC- and BC-oVEMP, thereby causing more deterioration of BC-oVEMP than AC-oVEMP.

5.3.4 Inter-Aural Asymmetry Ratio

The IAAR for BC-oVEMP was higher than for AC-oVEMP from the IO montage, indicating greater variability between ears and the mean IAAR for BC-oVEMP using IO montage (28.26%) approaches the clinical concern threshold of 30–35%, suggesting reduced clinical reliability (Rosengren et al., 2019). This may reflect poorer recording stability and increased susceptibility to variability in BC recordings using the IO montage. The BC stimulation produces vibrations that travel mechanically through the skull, and these vibrations can vary depending on where exactly the bone vibrator is placed on the mastoid. Even slight differences in transducer positioning between the two sides can change the intensity and direction of vibratory energy reaching the utricle, leading to differences in response amplitudes between ears and consequently higher IAAR values. Fröhlich et al. (2021) also reported greater asymmetry ratios for mastoid BC stimulation compared to forehead stimulation, suggesting that oVEMPs are highly sensitive to small variations in transducer placement. In addition, the transmission of vibratory energy through the skull is naturally variable across individuals because factors such as skull biomechanics, bone density, and transcranial attenuation differ from person to person as mentioned previously. These factors may contribute to the greater inter-aural variability observed with BC-oVEMP recordings.

5.4 Comparison of response parameters between AC-oVEMP and BC-oVEMP using BT montage

5.4.1 Response Rate

Similar to the IO montage, the AC-oVEMP from the BT montage continued to show higher response rates than BC-oVEMPs. As discussed in Section 5.3.1, mastoid-placed BC stimulation generates lower and more variable mechanical energy at the utricular level compared to AC stimulation. Additionally, the stimulus duration impacts BC-oVEMP more than the AC-oVEMP, which may have caused the difference between the modes. The present findings suggest that while the BT montage substantially improves BC-oVEMP detection rates compared to IO (84–80% vs. 58–54%), achieving 100% BC-oVEMP response rates in healthy young adults remains a challenge with mastoid stimulation using audiometric bone vibrators. The increase in BC-oVEMP response rates from 54–58% (IO montage) to 80–84% (BT montage) in healthy young adults suggests that the BT montage may be especially valuable in clinical populations where BC stimulation is the preferred or only viable option, such as individuals with middle ear pathology or conductive hearing loss. In such populations, the BT montage could substantially reduce the proportion of absent or uninterpretable BC-oVEMP responses, thereby improving the clinical utility of the test.

5.4.2 Absolute Latencies

The latency differences between AC and BC stimulation remained minimal. While BC-oVEMPs from BT montage had longer latencies of both peaks in both ears than AC-oVEMPs from the same montage, the difference was statistically significant only for n1 latency in left ear. This finding parallels with the findings of IO montage. The small effect size for the left ear finding also suggests that while statistically significant, the biological magnitude of this difference may not be clinically significant but the pattern of having shorter latency with AC stimulation remained similar. The difference may be dictated by a larger than optimal stimulus duration and rise/fall time for BC stimulus, as explained in the earlier section for the IO montage.

5.4.3 Peak-to-Peak Amplitude

The BT montage revealed a significantly higher peak-to-peak amplitude for AC-oVEMP compared to BC-oVEMP in both the right ear and left ear with small to medium effect sizes. The lower amplitudes observed for BC-oVEMP compared to AC-oVEMP in the present study may additionally reflect the limited output capability of the B71 bone vibrator and the reduced efficiency of mastoid stimulation in generating consistent utricular activation. Additionally, larger than the optimal BC stimulus duration and rise/fall time could have contributed to lower BC-oVEMP amplitudes.

5.4.4 Inter-Aural Asymmetry Ratio

The IAAR values obtained using the BT montage were lower and more stable for both AC and BC stimulation than the IO montage. IAAR for AC-oVEMP was 15.90% and BC-oVEMP was 23.12%. These findings have a similar pattern to that of the findings of the IO montage. The parallel pattern of higher BC-IAAR compared to AC-IAAR observed across both montages confirms that the increased asymmetry under BC stimulation is a stimulus-mode effect rather than montage-specific differences, likely reflecting the inherent variability of skull-transmitted vibration as described in Section 5.3.4.

The findings from the present study establish the BT electrode montage as superior to the IO electrode montage for both AC- and BC-oVEMP recording, adding proof to the prior evidences in the AC domain (Raveendran & Singh, 2024; Makowiec et al., 2019; Sandhu et al., 2013; Mat et al., 2023) and extending it to the BC domain.

Chapter VI

Summary & Conclusion

oVEMP responses are influenced by both stimulus-related factors (including the mode of stimulation) and recording-related parameters (including the electrode montage). While separate influence on mode of stimulation on responses from one montage (IO montage) are well understood, the understanding for the BT montage remains undercooked. Previous evidences have demonstrated that the BT electrode montage produces larger amplitude responses and higher response rates compared to the traditional IO montage for AC-oVEMP. However, the advantage of the BT montage over the IO montage for BC-oVEMP had not been consistently shown. Therefore, the present study was undertaken to investigate the effect of electrode montage on oVEMP's response parameters when elicited using air-conduction sound and bone-conduction vibration in healthy adults. The objectives were to compare the response rate, absolute latencies (n1 and p1), peak-to-peak amplitude, and IAAR of AC- and BC-oVEMP between BT and IO montages and also to compare the same response parameters between the AC and BC modes of stimulation.

The study recruited 50 adults aged 18–30 years with normal hearing sensitivity, normal middle ear function, and no vestibular symptoms or signs. All participants underwent comprehensive audiological and vestibular screening. oVEMP responses were recorded simultaneously from BT and IO electrode montages. AC-oVEMP and BC-oVEMP were elicited using 125 dB peSPL 500-Hz tone burst stimuli of rarefaction polarity delivered through an IP30 insert earphone and Radioear B71 bone vibrator, respectively. The analysis window was set to 70 ms, with band-pass filtering between 0.1 Hz and 1000 Hz. The participants maintained a gaze elevation of 30° in the mid-sagittal plane during the oVEMP recording.

The results demonstrated that in both AC-oVEMP and BC-oVEMP, the BT montage consistently showed higher response rates, larger amplitudes, and lower asymmetry ratios without significantly affecting latency measures. AC-oVEMP recordings showed better response rates, larger amplitudes, and lower IAAR values than BC-oVEMP for both electrode montages, indicating more robust and symmetric responses with air-conducted stimulation. These findings indicate that the BT montage may improve the clinical reliability and diagnostic utility of oVEMP recordings, regardless of whether AC or BC stimulation is used, as it consistently yields more robust, reliable, and symmetric responses than the IO montage. Overall, the present study found that the BT montage is a superior alternative to the conventional IO montage for oVEMP recording, both for AC and BC modes of stimulation.

6.1 Clinical Implications

The findings of the present study suggest that the BT montage may be a more effective electrode configuration than the traditional IO montage for recording both AC-oVEMP and BC-oVEMP responses. The BT montage consistently demonstrated higher response rates, larger amplitudes, and lower asymmetry ratios without significantly affecting latency measures. This would improve the sensitivity of the test by reducing the false negative responses, which may be falsely interpreted as vestibular pathology. These findings indicate that the BT montage may improve the clinical reliability and diagnostic utility of oVEMP recordings across both stimulation modes. The improved robustness of responses obtained using the BT montage may be particularly beneficial in clinical populations where responses are often reduced or absent, such as in vestibular neuropathy, superior semicircular canal dehiscence, Ménière’s disease, and age-related vestibular dysfunction. Further, the lower IAAR values obtained using the BT montage may improve the sensitivity of asymmetry-based clinical interpretation.

Overall, the present findings support the growing body of literature favouring the BT montage as a superior alternative to the conventional IO montage for oVEMP recording and the use of BC-oVEMP in clinical settings where BC stimulation is needed (e.g., patients with conductive hearing loss or absent AC-oVEMP). Clinically, adopting the BT montage for oVEMP recording, regardless of stimulation mode, would improve test sensitivity and reduce the rate of absent responses that might be misinterpreted as vestibular pathology.

6.2 Limitations and Future Directions

The present study was conducted exclusively on young healthy adults aged 18–30 years. Future studies should extend these findings to older adults and clinical populations with vestibular disorders such as Meniere's disease, superior canal dehiscence, and vestibular neuritis, to confirm the better clinical applicability of oVEMPs from the BT montage, or refute it.

The study compared only the BT and IO montages. Future studies should simultaneously compare all alternate electrode montages (BT, chin-referenced, sternum-referenced) under both AC and BC stimulation modes to provide a comprehensive understanding of the optimal electrode configuration for clinical use.

The present study primarily focused on conventional response parameters such as latency, amplitude, response rate, and IAAR. The study did not examine test-retest reliability of oVEMP responses from the two montages under the two stimulation modes. Future studies should assess the intra- and inter-reliability of BT and IO montage-recorded AC-oVEMP and BC-oVEMP; separately, as reliability is essential to comment on the clinical utility.

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Appendix

Institute Review Board approval for Bio-Behavioural Research proposal involving human subjects at AIISH.

All India Institute of Speech and Hearing
(An autonomous Institute under the
Ministry of Health and Family Welfare, Govt. of India)
Center of Excellence - Assessed & Accredited by NAAC with 'A' Grade
ISO 9001:2015 Implemented Institute
Manasagangothri, Mysuru-570006

ಅಖಿಲ ಭಾರತ ವಾಕ್ ಮತ್ತು ಶ್ರವಣ ಸಂಸ್ಥೆ
ಮಾನಸಗಂಗೋತ್ರಿ, ಮೈಸೂರು–570006
अखिल भारतीय वाक् श्रवण संस्थान
मानसगंगोत्री, मैसूरु - 570 006

INSTITUTE REVIEW BOARD (IRB) APPROVAL FOR BIO-BEHAVIOURAL RESEARCH PROPOSAL INVOLVING HUMAN SUBJECTS AT AIISH

AIISH Institute Review Board (IRB)

Ref: SH/IRB/M.4/AUD.40/2025-26 **Date: 06/01/2026**

Title of the Dissertation	: Comparison Of Air Conduction And Bone Conduction Ocular Vestibular-Evoked Myogenic Potential Recordings Using Infraorbital And Belly-Tendon Electrode Montages
Name of the Investigator	: Prasanna S
Guide	: Dr. Niraj Kumar Singh
Co-Guide (if any)	: Nil
Proposed Duration of the Project	: 08 months
Source of funding	: Non-funded Master's dissertation
Estimated budget	: Nil
Reference Number of the Project	: Nil
Date on which the IRB meeting was held	: 02.01.2026
A clear statement of the decision reached IRB meeting (In the vent of the proposal is not approved, a statement of reasons for the same must be indicated)	: **APPROVED**
Advice & suggestions (if any)	: NIL

Signature & Name of the Member Secretary-IRB
Dr. Animesh Barman
Professor of Audiology
All India Institute of Speech and Hearing, Mysore-570006

सदस्य सचिव / Member Secretary
Institutional Review Board
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