Cervical and ocular vestibular evoked myogenic potential: A comparison of narrowband chirp, broadband chirp, tone burst and click stimulation

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Abstract

Objectives: To compare the response rate and response parameters of cervical and ocular vestibular evoked myogenic potentials (c&oVEMP) elicited by narrowband (NB) and broadband (BB) CE-Chirp, with the more classical tone burst (TB) and click VEMPs.

Design: The response rate, latency, amplitude and asymmetry ratio of c&oVEMPs elicited by 95 dB nHL air conducted (AC) 500 Hz NB CE-chirp, BB CE-chirp, 500 Hz TB and click stimuli were recorded bilaterally.

Study sample: 20 male and 38 female participants (19–39 years).

Results: For the cVEMP, the highest response rate was found for NB chirp (100%), followed by TB (91%), BB chirp (87%) and finally click (85%). A similar order was seen for oVEMP with percentages of 100%; 57%, 57%, and 43%. The 500 Hz NB CE-Chirp elicited significantly shorter cVEMP P1 and N1 latencies and significantly larger c&oVEMP amplitudes compared to all other stimuli. BB CE-Chirp elicited significantly shorter c&oVEMP P1 and N1 latencies with smaller amplitudes compared to TB. Asymmetry ratios were not statistically significant for all comparisons.

Conclusion: The 500 Hz NB CE-chirp provides the highest response rates, shorter latencies and larger amplitudes, and therefore seem a promising stimulus for reliably measuring c&oVEMPs in clinical practice.

Keywords: Cervical VEMP, ocular VEMP, normative data, CE-Chirp, tone burst, click

Introduction

The vestibular evoked myogenic potential (VEMP) is a clinical vestibular function test used to assist in the identification and diagnosis of vestibular pathologies by evaluating otolith function (Ozgur et al. 2015; Walther and Cebulla 2016). The cervical VEMP (cVEMP) is mediated by a vestibulocervical reflex pathway that includes the saccular macula, inferior vestibular nerve, the lateral vestibular nucleus, the lateral vestibulospinal tract, and the motor-neurons of the ipsilateral sternocleidomastoid (SCM) muscle (Akin, Murnane, and

Proffitt 2003). Vestibular evoked myogenic potentials can also be recorded from extraocular muscles, as part of the linear vestibulo-ocular reflex pathway by placing electrodes around the eyes and is referred to as ocular VEMP (oVEMP), which predominantly reflects utricular function (Rosengren, Welgampola, and Colebatch 2010).

The most common VEMP parameters used for interpretation include the P1 latency, N1 latency, VEMP threshold, asymmetry ratio and P1-N1 amplitude (Isaradisaikul et al. 2012). Initially cVEMPs were recorded using air conduction (AC) click stimuli (Colebatch, Halmagyi, and Skuse 1994). Murofushi, Matsuzaki, and Wu (1999) later reported that cVEMPs could also be evoked by a 500 Hz tone burst (TB) stimulus and resulted in larger amplitudes compared to higher frequencies. Subsequently the AC TB stimulus between 500 Hz and 1000 Hz has been reported to result in larger amplitudes (Akin, Murnane, and Proffitt 2003; Singh et al. 2014), greater reliability and smaller inter-laboratory variability (Meyer, Vinck, and Heinze 2015) than the click stimulus and is therefore the preferred stimulus to reliably perform cVEMPs. The largest oVEMP response amplitudes were also elicited around 400-800 Hz when using an AC TB stimulus (Rosengren, Welgampola, and Colebatch 2010). However, reliable AC recordings for oVEMPs can be difficult to obtain since their response is approximately 1/50th of the amplitude of the cVEMP (Halmagyi and Carey 2010). Several studies have reported greater oVEMP response rates and amplitudes to bone conduction (BC) stimulation through electromechanical vibrators, such as the minishaker (type 4810, Bruel and Kjaer) (Cheng et al. 2009; Wang et al. 2010) and this has become the gold standard for oVEMP testing in laboratory settings.

In an attempt to improve the identification of oVEMP responses, several studies have suggested varying electrode montage configurations (Sandhu, George, and Rea 2013; Govender et al. 2016; Leyssens et al. 2017). The standard oVEMP electrode montage involves placing an active electrode below the midpoint of the eye and a reference electrode approximately 1-2 cm below the active electrode. Sandhu, George, and Rea (2013) coined the terms “belly-tendon” or “nose configuration” montage when they discovered that an active electrode placed just lateral to the standard electrode placement and the reference electrode placed at the medial canthus resulted in larger oVEMP amplitudes. This was further corroborated by Govender et al. (2016) and Leyssens et al. (2017). Piker et al. (2018) reported that the medial canthus reference electrode position is not electrically indifferent. The researchers stated that reference contamination possibly results in the increased oVEMP amplitude obtained when using the belly-tendon montage and that there is insufficient evidence to recommend this montage for oVEMP testing. To avoid reference contamination, in the presence of small oVEMP amplitudes, a chin or a noncephalic reference may provide a more indifferent reference location (Piker et al. 2011). Both Sandhu, George, and Rea (2013) and Govender et al. (2016) reported smaller oVEMP amplitudes when the active electrode was placed on the lateral canthus of the eye in response to 500 Hz AC TB and BC stimuli. There is limited research available for the lateral and medial variations as these have not been comprehensively explored.

More recently, the newly introduced CE-Chirp stimulus has yielded positive outcomes, resulting in larger amplitudes (Walther and Cebulla 2016) and shorter latencies for cVEMP (Wang et al. 2014; Ozgur et al. 2015; Murofushi et al. 2020) and oVEMP (Bas et al. 2020). The CE-Chirp was designed in an attempt to increase the temporal synchrony within the auditory

system (Elberling and Don 2010). The term CE-Chirp is a registered trademark by the Danish company, Interacoustics, for their development of a CE-Chirp family of short duration acoustic stimuli that can be used in evoked potential testing. There has already been substantial evidence to support the use of the AC chirp stimulus in lieu of click and TB stimuli for auditory brainstem response (ABR) testing and auditory steady state response (ASSR) testing (Elberling and Don 2010; Rodrigues and Lewis 2012; Speidel and Beck 2016).

The chirp is flexible and can be designed in various frequency ranges. This includes the broadband (BB) CE-Chirp, comprising of a frequency range of 500–8000 Hz, and four octave-band chirps (500, 1000, 2000 and 4000 Hz) (Wang et al. 2014). These octave-band chirps are referred to as narrowband (NB) chirps and is defined as "a chirp which includes any desired frequency range apart from those frequencies which it is specified to exclude" (Cebulla and Walther 2019, 175). The literature suggests that the 500 Hz NB chirp is the optimal frequency to elicit VEMP responses as saccule tuning is enhanced at 500 Hz (Walther and Cebulla 2016; Cebulla and Walther 2019). Walther and Cebulla (2016) designed a chirp stimulus ranging from 250 to 1000 Hz and found significantly larger c&oVEMP amplitudes with greater stability compared to click and 500 Hz tone burst stimulation in healthy participants. Cebulla and Walther (2019) found the highest cVEMP amplitudes for both sequential and quasi-simultaneous narrow band chirps at 500 Hz followed by 1, 2000 and 4000 Hz. Moinudeen, Varshini, and Wesley (2020) also reported significantly larger amplitudes and shorter latencies for cVEMP evoked by 500 Hz NB CE-Chirp compared to 500 Hz TB.

Wang and colleagues (2014) compared a BB CE-Chirp (200 – 10,000 Hz), optimised for ABR testing, to click and 500 Hz TB stimulation for cVEMPs in persons with normal hearing and no history of vestibular disease. They found the chirp evoked cVEMP latency to be approximately 7 ms shorter to that of the cVEMP evoked by the 500 Hz TB stimulus and observed significantly larger P1-N1 amplitudes for chirp evoked cVEMP compared to the 500 Hz TB stimulus. Ozgur et al. (2015) also compared the difference in response characteristics of the cVEMP using AC 500 Hz TB, click and NB chirp (500 – 4000) stimuli. It was found that P1 and N1 latencies induced by the chirp stimulus proved to be significantly shorter when compared to the click and 500 Hz TB stimuli. The 500 Hz TB stimulus resulted in waves with longer latencies in the presence of greater amplitudes, whereas the chirp stimulus resulted in waves with shorter latencies in the presence of smaller amplitudes. More recently, Murofushi et al. (2020) compared cVEMP responses evoked by 500 and 1000 Hz TB to the CE-Chirp LS, which is a modified version of the original CE-Chirp and found shorter latencies and smaller amplitudes for CE-Chirp LS compared to the 500 Hz TB. Bas and colleagues (2020) reported that oVEMPs elicited by a BB chirp stimulus resulted in shorter latencies and higher amplitudes when compared to click and TB stimuli.

There is little research to clearly depict the clinical applicability of the AC chirp stimulus in VEMP recordings, even though several studies have been conducted using chirp stimuli in ABR and ASSR recordings with favourable outcomes (Elberling and Don 2010; Rodrigues and Lewis 2012; Speidel and Beck 2016). Furthermore, the available literature on chirp evoked VEMPs lacks consensus on which type of chirp stimulus should be used, i.e. BB chirp or NB chirp. For this reason, the aim of this study was to compare response rates and amplitude and latency parameters for cervical and ocular VEMP elicited by 500 Hz NB CE-Chirp, BB CE-Chirp, 500 Hz TB and click stimuli.

Method

Ethical clearance and informed consent

Ethical approval was obtained from the University of Pretoria Research and Ethics Committee of the Faculty of Humanities (approval number GW20170407HS) prior to the commencement of the data collection. All participants provided written and verbal informed consent.

Study design

A quantitative, exploratory research design of analysis was used. In addition, a purposive sampling method was used to recruit participants in this study.

Participants

Twenty male and 38 female participants, ranging from 19 to 39 years of age, with a mean age of 25 years (SD ± 5.208), participated in the study. This age range was selected to exclude the effects of age-related hearing loss and/or vestibular dysfunction. Four participants were excluded from the analysis of the cVEMP data and 9 participants were excluded from the analysis of the oVEMP data as they presented with no response to all four stimuli at 95 dB nHL due to undetermined reasons. As a result, all participants included in the study, had a present cVEMP and oVEMP result for at least one or more of the test stimuli. In addition, all participants were required to present with no history of hearing loss, vestibular or neurological disorders. This was ensured by participants completing a case history questionnaire on the day of testing which comprised of both open and close-ended questions regarding their biographical, family, medical, auditory, vestibular, occupational and recreational history. Behavioural pure tone audiometry and immittance testing was also completed on the day of testing to ensure hearing sensitivity and middle ear function, respectively, fell within normal limits prior to data collection.

Procedures

Each participant underwent a bilateral otoscopic examination to exclude outer ear pathologies. Tympanometry (y-226 Hz), acoustic reflex testing (MT10, Interacoustics, Denmark) and pure tone air conduction audiometry (Kuduwave, eMoyo, South Africa) were conducted to exclude conductive and sensorineural hearing loss. All participants were required to present with pure tone air conduction audiometry thresholds within the normal limit of −10–25 dB HL across the frequency range (Gelfand 2001). All data was collected in a single session for each participant. The Interacoustics Eclipse EP25 two-channel VEMP system (Interacoustics, AS, Assens, Denmark) was used to conduct cVEMPs and oVEMPs on all participants. All equipment used in the study was calibrated prior to the commencement of data collection. The Interacoustics Eclipse was calibrated by a trained technician according to output level, frequency, and time (Wilber 2002) and certified under ISO 13485:2003 which specifies requirements for medical devices.

The cVEMP response was recorded by placing a non-inverting electrode at the midpoint of the left and right sternocleidomastoid (SCM) muscle, the inverting electrode was placed on the upper sternum and the ground electrode on the forehead. This electrode montage is

proposed by Colebatch, Halmagyi, and Skuse (1994). Non-disposable silver disc electrodes were used. The participants were seated with their head rotated 45 degrees to the opposite side of the test ear. Electromyography (EMG) was used to ensure equal and sustained contraction of the SCM muscle and to minimise the effect of muscle contraction on the cVEMP amplitude. The EMG was measured using the same electrode used to record the cVEMP response. The EMG activity was measured by the participants self-monitoring their EMG activity and the use of a mathematical correction for amplitude normalisation of the right and left cVEMP response (McCaslin, Fowler, and Jacobson 2014). The participants were required to monitor and maintain their muscle contraction within a lower (50 μV) and upper (150 μV) limit via an external EMG monitor. The EMG measurement method should be stipulated in research papers as the type of mathematical correction used could result in marginally different values (Rosengren et al. 2019). According to the equipment specifications the mean rectified EMG for each sweep of recording was calculated from a 100 ms pre-stimulus period and a root mean square (RMS) of the rectified EMG was determined. The Interacoustics Eclipse records the cVEMP response amplitude as the pre-stimulus EMG minus the EMG recorded when the stimulus is presented, i.e. if the pre-stimulus EMG is recorded at 100 μV and when the stimulus is applied the EMG is recorded at 48 μV, this will result in a cVEMP response amplitude of 52 μV. This ensures that the cVEMP response, following the presentation of the stimulus, is not included in the average EMG contraction.

The oVEMP response was recorded by placing the non-inverting electrode on the lateral canthus of the eye contralateral to the stimulated ear (Sandhu, George, and Rea 2013; Govender et al. 2016); the inverting electrode on the chin to avoid reference contamination (Piker et al. 2011) and the ground electrode on the forehead (Todd et al. 2007). Non-disposable silver disc electrodes were used. The participants were seated and asked to look up at a reference on the ceiling to maintain maximal upward gaze for the duration of the test.

For both cVEMPs and oVEMPs, a rarefaction 500 Hz NB CE-Chirp stimulus (duration 9 ms, 95 dB nHL equivalent to 120.5 dB peSPL), BB CE-Chirp stimulus (200 Hz–11,000 Hz; duration 8 ms, 95 dB nHL equivalent to 126.5 dB peSPL), 500 Hz TB stimulus (rise/fall time = 2 ms, plateau time = 2 msec, 95 dB nHL equivalent to 118.5 dB peSPL) and a click stimulus (duration 8 ms, 95 dB nHL equivalent to 130.0 dB peSPL) were presented to each ear via insert earphones (EAR 3 A, Etymotic research, USA) and ER3-14B disposable foam eartips. A bandpass filter of 10-1000 Hz was utilised for both oVEMP and cVEMP recordings. An artefact rejection level of 800 μV was used for cVEMP and 400 μV for oVEMP.

The stimulus was presented twice, with averaging of the response to 100–150 stimulus repetitions for cVEMPs and 500 repetitions for oVEMPs. Rosengren et al. (2019) state that cVEMP recordings typically require approximately 100–200 stimulus repetitions and the authors recommend two trials of at least 150–200 stimuli repetitions when cVEMP responses are small or absent. As the oVEMP response is approximately 1/50th the amplitude of the cVEMP response (Halmagyi and Carey 2010) and contains more artefacts from periocular and facial muscles (Rosengren et al. 2019) longer averaging is required. As a result, 500 stimulus repetitions were used in the current study. The participants rested between stimuli to prevent muscle fatigue. A VEMP wave reproducibility rate of >85% was accepted. This wave reproducibility score is an automatic calculation in the VEMP software and aims to establish

the quality and reliability of the VEMP response within a specific time frame of 5 to 25 ms (Interacoustics A/S 2020).

All waveforms for each participant were recorded and marked by a trained audiologist. A cVEMP and oVEMP response was determined to be 'present' when a biphasic waveform within the specified time frame could be recorded. A response rate was determined for each stimulus by calculating the percentage of present responses. The first positive peak on the waveform was marked P1 and first negative deflection was marked N1 for cVEMPs. The first negative peak in the waveform was marked N1 and the first positive deflection was marked P1 for oVEMPs. The P1 latency; N1 latency; P1-N1 amplitude and asymmetry ratio were recorded for each stimulus. The asymmetry ratio calculation outlined by Akin and Murnane (2008) was utilised, i.e. [(AL – AR)/(AL + AR)] x 100. AL refers to the amplitude of the left ear and AR refers to the amplitude of the right ear.

Data analysis

Descriptive and inferential statistical analyses were used in this study. Data is presented as mean ± standard deviation (SD). All statistical analysis was performed using IBM SPSS (version 26) software for Windows. The distribution of the data was determined by the test of skewness, visual inspection of Q-Q plots and by conducting the Kolmogorov-Smirnov test across all variables of the study for each stimulus bilaterally. The data was found to be normally distributed for both cVEMP ($K = 0.07 - 0.284$, $p < 0.05$) and oVEMP ($K = 0.09 - 0.43$, $p < 0.05$) and parametric statistics were utilised in the analysis of the data. A value of $p < 0.05$ was accepted as statistically significant.

A paired samples t-test was used to determine whether a statistically significant difference existed between the right and left ear results for each stimulus. A statistical difference was not observed between the right and left ear results. Due to this statistical independence between the two ears, the data for the right and left ears were pooled for analysis (Coren and Hakstian 1990). An independent samples t-test was used to determine gender differences across VEMP parameters. Levene's Test for equality of variance showed that equal variances could be assumed for each variable tested. A paired samples t-test was used to compare the means for P1 latency, N1 latency, P1-N1 amplitude and the asymmetry ratio of cVEMP and oVEMP evoked by 500 Hz NB CE-Chirp compared to BB CE-Chirp, 500 Hz TB and click stimuli. Additionally, a paired samples *t*-test was used to compare the means for P1 latency, N1 latency, P1-N1 amplitude and the asymmetry ratio of cVEMP and oVEMP evoked by BB CE-Chirp compared to 500 Hz TB and click stimuli.

Results

Data for 54 participants were analysed for cVEMPs (34 female). Data for 49 participants were analysed for oVEMPs (32 female). There were no statistically significant differences between the right and left ears with regards to the cVEMP and oVEMP latency and amplitude ($p > 0.05$) parameters. With regards to gender, there were no statistically significant differences between male and female participants for cVEMP and oVEMP latency and amplitude parameters ($p > 0.05$). Therefore, the results of both genders and ears were pooled in the analysis of the data. The cVEMP and oVEMP results were presented separately.

Table 1. cVEMP response rate, latency, P1-N1 amplitude and asymmetry ratio for 500 Hz NB CE-Chirp, BB CE-Chirp, 500 Hz TB and click stimuli at 95 dB nHL**.**

		Parameters (mean ± *SD*)			
Stimulus Type	Response Rate	P1 (ms)	N1 (ms)	P1–N1 amplitude (μV)	Asymmetry ratio (%)
500 Hz NB CE-Chirp	100% ($n = 54$)	11.12 ± 2.80	17.52 ± 2.54	74.99 ± 35.87	13 ± 11
BB CE-Chirp	87% ($n = 47$)	15.96 ± 2.65	21.64 ± 2.20	46.19 ± 21.76	14 ± 11
500 Hz TB	91% ($n = 49$)	18.53 ± 2.92	25.98 ± 3.17	70.46 ± 35.60	16 ± 13
Click	85% ($n = 46$)	16.08 ± 2.79	21.67 ± 2.58	42.46 ± 18.72	15 ± 11
		[mean +/− 1.96 *SD*]	[mean +/− 1.96 *SD*]	[mean +/− 1.96 *SD*]	[mean +/− 1.96 *SD*]

Hz: Hertz; NB: Narrowband; BB: Broadband; TB: Toneburst; ms: milliseconds; μV: microvolts.

cVEMP

Data for 108 ears were analysed. The 500 Hz NB CE-Chirp response rate was the highest, followed by 500 Hz TB, BB CE-Chirp and, lastly, the click stimulus. Table 1 shows the response rate, mean ± SD of the P1 latency, N1 latency, P1-N1 amplitude and asymmetry ratios for each stimulus.

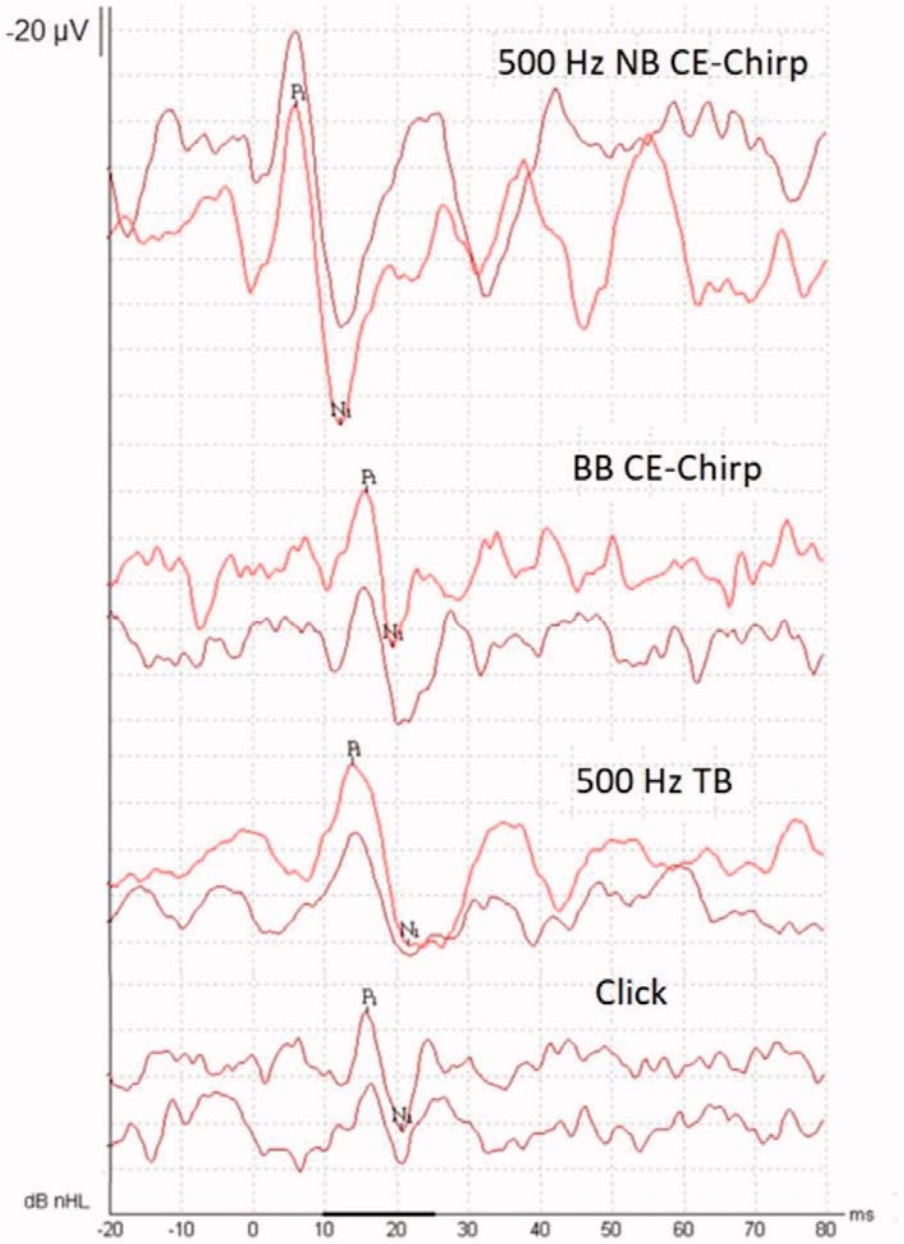

Figure 1. cVEMP wave examples for 500 Hz NB CE-Chirp, BB CE-Chirp, TB and Click stimuli.

The mean P1 and N1 latencies of cVEMP evoked by the 500 Hz NB CE-Chirp were significantly shorter ($p < 0.001$) than the P1 and N1 latencies of the BB CE-Chirp ($t = -21.060$; $t = -18.585$,

respectively), 500 Hz TB (t = −26.807; t = −26.526) and click (t = −18.296; t = −14.467) stimuli. The 500 Hz NB CE-Chirp also elicited significantly larger P1-N1 amplitudes compared to the BB CE-Chirp (t = 9.624; p < 0.001*)*, click (t = 11.040; p < 0.001*)* and 500 Hz TB stimuli (t = 2.146; p = 0.03). A statistically significant difference was obtained when the P1 latency (t = −8.776; p < 0.001), N1 latency (t = −13.614; p < 0.001) and P1-N1 amplitude (t = −7.326; p < 0.001) of the BB CE-Chirp was compared to the 500 Hz TB stimulus. A statistically significant difference was not obtained when the P1 latency (t = −0.831*;* p = 0.408), N1 latency (t = −0.473*;* p = 0.637) and P1-N1 amplitude (t = 1.892; p = 0.062) of the BB CE-Chirp was compared to the click stimulus. Characteristic waveforms, with corrected amplitudes, at an intensity level of 95 dB nHL for the four different stimulation types are presented in Figure 1.

The asymmetry ratios were not statistically different when the 500 Hz NB CE-Chirp was compared to the BB CE-Chirp, 500 Hz TB and click stimuli and when the BB CE-Chirp was compared to the 500 Hz TB and click stimuli.

oVEMP

Data for 98 ears were analysed. The 500 Hz NB CE-Chirp response rate was the highest, followed by 500 Hz TB and BB CE-Chirp and, lastly, the click stimulus. Table 2 shows the response rate, mean ± SD of the N1 latency, P1 latency, N1-P1 amplitude and asymmetry ratios for each stimulus.

The mean N1 and P1 latencies of oVEMP evoked by the 500 Hz NB CE-Chirp and BB CE-Chirp were significantly shorter than the N1 and P1 latencies evoked by the 500 Hz TB (p < 0.001) stimulus. Significantly shorter N1 (t = −3.985; p = 0.008) and P1 (t = −3.638; p = 0.038) latencies evoked by the 500 Hz NB CE-Chirp compared to the BB CE-Chirp were also obtained. A significant difference was not obtained when the N1 (t = −1.798; p = 0.081) and P1 (t = −1.004; p = 0.321) latencies of the 500 Hz NB CE-Chirp were compared to the click stimulus. Similarly, a significant difference was not obtained when the N1 (t = −0.122; p = 0.904) and P1 (t = 0.297; p = 0.768) latencies of the BB CE-Chirp were compared to the click stimulus. With regards to N1-P1 amplitude, the 500 Hz NB CE-Chirp elicited significantly larger amplitudes compared to the BB CE-Chirp (t = 3.123*;* p = 0.003), 500 Hz TB (t = 4.140; p < 0.001) and click (t = 3.581; p < 0.001) stimuli. A significant difference was not observed when the N1-P1 amplitude of the BB CE-Chirp was compared to the 500 Hz TB (t = 0.090; p = 0.929) and click (t = 0.911; p = 0.370) stimuli. Characteristic waveforms, at an intensity level of 95 dB nHL for the four different stimulation types are presented in Figure 2.

The asymmetry ratios were not statistically different when the 500 Hz NB CE-Chirp was compared to the BB CE-Chirp, 500 Hz TB and click stimuli and when the BB CE-Chirp was compared to the 500 Hz TB and click stimuli.

Table 2. oVEMP response rate, latency and N1–P1 amplitude for 500 Hz NB CE-Chirp, BB CE-Chirp, 500 Hz TB and click stimuli at 95 dB nHL.

		Parameters (mean ± SD)			
Stimulus Type	Response Rate	N1 (ms)	P1 (ms)	N1–P1 amplitude (μV)	Asymmetry ratio (%)
500 Hz NB CE-Chirp	100% ($n = 49$)	8.34 ± 3.59	12.68 ± 3.79	4.87 ± 2.66	13 ± 11
BB CE-Chirp	57% ($n = 28$)	11.26 ± 1.84	15.20 ± 2.24	3.81 ± 1.89	12 ± 8
500 Hz TB	57% ($n = 28$)	12.50 ± 2.48	16.62 ± 2.89	3.51 ± 1.29	12 ± 7
Click	43% ($n = 21$)	11.11 ± 2.46	14.85 ± 3.07	3.39 ± 1.57	14 ± 9
		[mean +/− 1.96 SD]	[mean +/− 1.96 SD]	[mean +/− 1.96 SD]	[mean +/− 1.96 SD]

Hz: Hertz; NB: Narrowband; BB: Broadband; TB: Toneburst; ms: milliseconds; μV: microvolts.

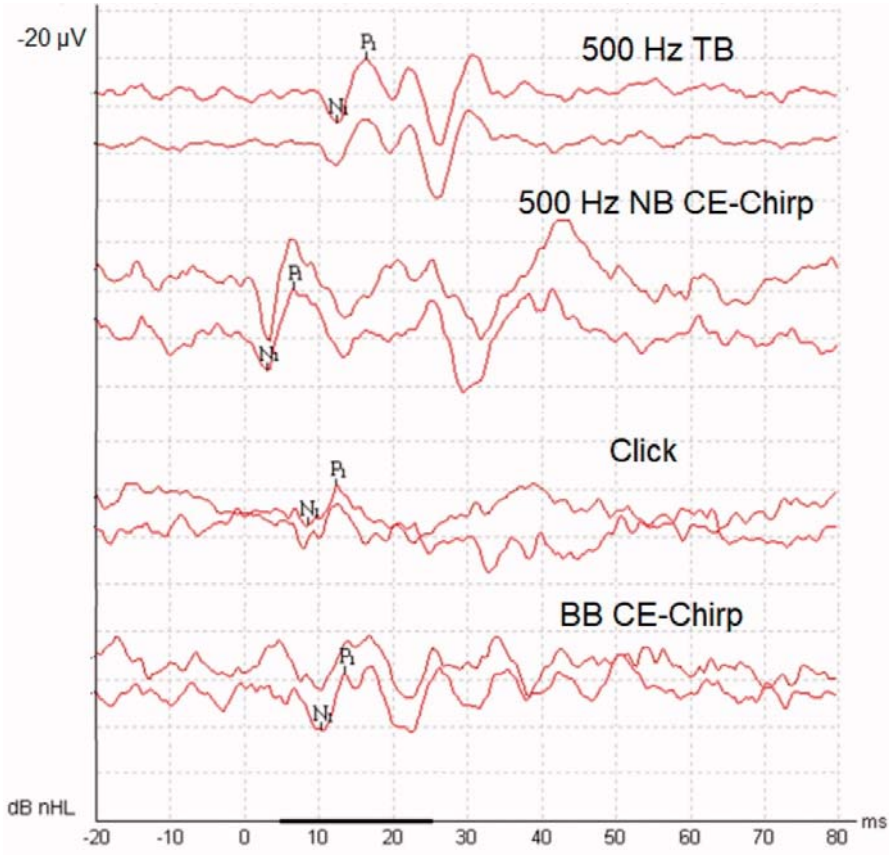

Figure 2. oVEMP wave examples for 500 Hz NB CE-Chirp, BB CE-Chirp, TB and Click stimuli.

Discussion

Since there is still no consensus on the type of chirp stimulus, parameters and normative data to be used in the VEMP interpretation, the aim of this study was to compare response rates and amplitude and latency parameters for cervical and ocular VEMP elicited by NB CE-Chirp, BB CE-Chirp, TB and click stimuli.

Response rate

The highest response rate obtained in the current study was for c&oVEMP evoked by the 500 Hz NB CE-Chirp (100%). Comparable to the current study, the available literature reports a response rate ranging from 86% to 100% for cVEMPs evoked by 500 Hz TB and click stimuli (Akin, Murnane, and Proffitt 2003; Isaradisaikul et al. 2012; Wang et al. 2014; (Blakley and Wong 2015; Ozgur et al. 2015). It has been well documented that response rates increase with an increase in intensity. However, it is also evident that even at increased intensities of 100 dB nHL, it is still possible that a 100% response rate may not be obtained for cVEMP evoked by TB and click stimuli (Blakley and Wong 2015; Ozgur et al. 2015). Recently, concerns about the effect of these high intensity (> 100 dB nHL) stimulation levels on cochlear vulnerability have been raised (Verrecchia et al. 2019). In the current study, cVEMP evoked

by the 500 Hz NB CE-Chirp elicited the highest response rate (100%) at a lower intensity level of 95 dB nHL when compared to BB CE-Chirp, 500 Hz TB and click stimuli, as opposed to previous studies which relied on a higher intensity level of 100 dB nHL. This suggests that frequency specific NB chirps may provide an alternative for cVEMPs to be elicited at safer AC intensity levels, reducing the risk of cochlear changes, in clinical settings.

The oVEMP response rate has also proven to be variable in response to AC TB and click stimuli, ranging between 80% and 100% (Cheng et al. 2009; Wang et al. 2010; Rosengren, Govender, and Colebatch 2011). Rosengren, Govender, and Colebatch (2011) suggested that there may be insufficient activation of utricular fibres in response to AC stimuli which could account for the reduced oVEMP response rate and amplitude. As a result, oVEMPs evoked by AC TB and click stimuli do not form a routinely integrated diagnostic component in clinical settings as part of the vestibular test battery, even though there is evidence to depict their clinical utility (Nguyen et al. 2010; Zuniga et al. 2013; Bas et al. 2020). It has, however, been well documented that oVEMPs evoked by BC stimuli result in higher response rates and greater amplitudes than AC stimuli (Cheng et al. 2009; Wang et al. 2010; Rosengren, Govender, and Colebatch 2011; Kantner and Gurkov 2012). Electromechanical vibrators, such as the minishaker (type 4810, Bruel and Kjaer), have proven to be most effective with response rates ranging from 90% to 100% (Cheng et al. 2009; Wang et al. 2010). However, in addition to being costly, the minishaker is currently not certified for clinical use and is restricted to laboratory applications (Dlugaiczyk 2020). Therefore, the results of the current study with a 100% response rate for AC 500 Hz NB CE-Chirp seems promising and may provide an alternative to AC TB and click stimuli, at lower intensity levels, in clinical settings where the minishaker is not readily available. These high numbers were also confirmed by a study of Bas et al. (2020) with a 98.8% response rate.

VEMP parameters: P1 latency, N1 latency and amplitude

The results of this study revealed that a frequency specific 500 Hz NB CE-Chirp produced the shortest latencies and largest amplitudes for cVEMP and oVEMP when compared to BB CE-Chirp, 500 Hz TB, and click stimuli. This difference in latency between the four stimulus types may be related to the stimulus shape and rise time. Previous studies have demonstrated that the wave V latency of the BB chirp-evoked ABR was comparable to that of the click-evoked ABR (Speidel and Beck 2016). It was reported that the frequency spectrum (200 − 8000 Hz) of the BB CE-Chirp and click are similar but with different time domains (Wang et al. 2014). Similarly, in the current study, it was observed that both cVEMP and oVEMP evoked by BB CE-Chirp resulted in P1 and N1 latencies that were comparable to those evoked by the click stimulus. However, Bas et al. (2020) found that the wideband chirp (10 − 10 000 Hz) produced significantly shorter oVEMP latencies than both 500 Hz TB and click stimuli. The authors suggested that chirp evoked VEMP latencies were shorter due to the similar frequency specific tonotopic organisation of the irregular neurons in the utricle as seen in the cochlea. Wang et al. (2014) proposed that the CE-Chirp results in improved synchronisation of the basilar membrane impulses, causing increased movement of endolymph fluid which, in turn, allows the CE-Chirp to stimulate the sacculus more effectively, resulting in shorter cVEMP latencies. This was observed in the current study as the cVEMP P1 and N1 latencies evoked by the 500 Hz NB CE-Chirp were shorter than that of the P1 latency evoked by the 500 Hz TB by 7.41 ms and N1 latency evoked by the 500 Hz TB by 8.64 ms. In addition to the improved

synchronisation of the basilar membrane, the NB CE-Chirp stimulus is also designed by equipment manufacturers with early onset timing compared to TB, resulting in shorter latencies (Speidel and Beck 2016). This was confirmed by Zakaria et al. (2015) who compared the 500 Hz TB to a customised chirp with no onset/offset temporal adjustment and found no significant latency differences between the two stimuli, suggesting that any latency differences are due to the chirp design and not physiologic factors. Furthermore, Felipe et al. (2016) suggested that, due to the TB rise time, there is a delay in the attainment of the maximum TB intensity, producing multiple firings of vestibular neurons to one TB stimulus, resulting in delayed cVEMP latencies. It was with this concept in mind, that the chirp stimulus was originally designed, in an attempt to increase the neural synchrony within the auditory system and compensate for the time delay which was obtained when a brief stimulus, such as the TB or click, was used (Elberling and Don 2010). Although the oVEMP evoked by 500 Hz NB CE-Chirp elicited shorter N1 and P1 latencies than the 500 Hz TB in the current study, a greater standard deviation was observed for the 500 Hz NB CE-Chirp, suggesting greater variation from the mean. Recently, Montesdeoca et al. (2021) investigated a new technique to record cVEMP latencies by direct vestibular electrical stimulation following vestibular implantation. The authors reported P1 and N1 latencies of 11.33 − 13.6 ms and 18.33 − 21 ms, respectively, which is shorter than the previously reported latencies by acoustic stimulation using TB and click stimuli.

In addition to significantly shorter P1 and N1 latency values, frequency specific chirp evoked VEMPs have also produced larger P1-N1 amplitudes for cVEMP (Wang et al. 2014; Walther and Cebulla 2016; Moinudeen, Varshini, and Wesley 2020) and N1-P1 amplitudes for oVEMP (Bas et al. 2020). Wang et al. (2014) attributed the amplitude differences between the chirp, TB and click to the different frequency composition of each stimulus. The TB is a short, single frequency stimulus, whereas the chirp consists of a certain band of frequencies (Moinudeen, Varshini, and Wesley 2020). Therefore, the frequency specific chirp stimulus induces greater stimulation of the irregular afferent neurons, resulting in increased amplitudes compared to TB and click stimuli (Bas et al. 2020).

Recently, Moinudeen, Varshini, and Wesley (2020) reported significantly larger cVEMP P1-N1 amplitudes for 500 Hz NB chirp (70.15 ± 25.45 μV) compared to 500 Hz TB (68.45 ± 28.11 μV). The mean P1-N1 cVEMP amplitudes in the current study were similar to those reported by Moinudeen and colleagues for 500 Hz NB CE-Chirp (74.99 ± 35.87 μV) and 500 Hz TB (70.46 ± 35.60 μV) with the 500 Hz NB CE-Chirp also producing significantly larger amplitudes than TB. Compared to the amplitudes in the current study, Ozgur et al. (2015) reported smaller cVEMP amplitudes (33 ± 18.6 μV) than those observed in the current study, when using a chirp stimulus (500–4000 Hz) designed for diagnostic audiological assessments compared to 500 Hz TB and click stimuli. Wang et al. (2014) also utilised a chirp stimulus (200–10,000 Hz) designed for diagnostic audiological assessments and reported smaller amplitudes of 14.422 ± 5.505 μV compared to the results of the current study. As a result, Walther and Cebulla (2016) designed a chirp specifically for cVEMP testing and reported greater cVEMP amplitudes of 233.4 ± 117.9 μV. Although these previous studies utilised chirps in different bands compared to TB and click stimuli, there are no previous studies comparing the cVEMP amplitude of the NB CE-Chirp to the BB CE-Chirp. In the current study, the 500 Hz NB CE-Chirp elicited significantly larger P1-N1 amplitudes compared to the BB CE-Chirp (46.19 ± 21.76 μV),

suggesting that the 500 Hz NB CE-Chirp may be a more suitable stimulus than BB CE-Chirp in the identification of the cVEMP response.

The 500 Hz NB CE-Chirp elicited significantly larger N1-P1 amplitudes (4.87 ± 2.66 μV) compared to all other stimuli in the current study. Walther and Cebulla (2016) also reported the highest oVEMP N1-P1 amplitudes evoked by a chirp stimulus (250 − 1000 Hz) specifically designed for VEMP testing compared to TB and click stimuli. However, the authors reported smaller amplitudes for oVEMP evoked by this constructed chirp stimulus (3.5 ± 0.72 μV), 500 Hz TB (2.9 ± 2.84 μV) and click (2.2 ± 0.54 μV) to that of the current study. Recently, Karacayli et al. (2020) reported much larger N1-P1 amplitudes of 17.08 ± 13.41 μV and 16.25 ± 11.75 μV for the right and left ear, respectively, for oVEMPs evoked by 500 Hz NB chirp with the negative electrode placed on the inferior oblique muscle and the reference electrode placed on the chin. The data for the right and left ears were pooled in the current study, however, Karacayli et al. (2020) reported ear specific data, which also revealed significantly larger N1-P1 amplitudes for oVEMP evoked by the 500 Hz NB CE-Chirp compared to 500 Hz TB bilaterally. This suggests that further research is needed to investigate oVEMP evoked by a 500 Hz NB CE-Chirp with different electrode montage configurations to compare the effect on N1-P1 amplitude responses. Nevertheless, the present study clearly indicates that, if the minishaker is not available, the AC 500 Hz NB CE-Chirp may provide a suitable option with a high response rate and increased amplitudes.

The final VEMP parameter investigated in this study was the asymmetry ratio which is used clinically in the diagnosis of unilateral vestibular pathologies by comparing the amplitude of each ear. No significant difference was obtained when the asymmetry ratios of the 500 Hz NB CE-Chirp were compared to BB CE-Chirp, 500 Hz TB or click, or when the BB CE-Chirp was compared to the 500 Hz TB and click stimuli. Similar findings were reported in the literature (Wang et al. 2014; Ozgur et al. 2015; Bas et al. 2020; Karacayli et al. 2020). This suggests that there is no clear advantage of stimulus type with regards to asymmetry ratio.

Conclusion

The results of this study indicate that c&oVEMPs evoked by the 500 Hz NB CE-Chirp provide the highest response rates, shorter P1 and N1 latencies, and overall, larger VEMP amplitudes when compared to the BB CE-chirp stimulus and the more conventional TB and click stimuli. Therefore, the NB CE-Chirp seems a promising stimulus to reliably estimate saccular and utricular function in clinical practice. The clinical application of the findings of this study are limited as it did not include patients who presented with peripheral vestibular dysfunction. The study did not draw comparisons between a control group and a group consisting of patients with a confirmed diagnosis of peripheral vestibular dysfunction. Therefore, c&oVEMP studies investigating peripheral vestibular disorders are required to determine the clinical applicability of the NB CE-Chirp stimulus.

Disclosure statement

No potential conflict of interest was reported by the author(s).

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