Optimizing Ocular Vestibular Evoked Myogenic Potentials With Narrow Band CE-Chirps

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Objectives: To evaluate the effects of narrow band CE-Chirp (NB CE-Chirp) on the amplitudes and latencies in ocular vestibular evoked myogenic potentials (oVEMPs) at 500 and 1000 Hz in comparison with tone burst (TB).

Design: Twenty-one healthy volunteers were included in the study and tested in air conduction with a "belly-tendon" montage. Recording conditions were randomized for each participant and each modality was tested twice to check the reproducibility of the procedure.

Results: NB CE-Chirps at 500 Hz revealed larger n1-p1 amplitudes than 500 Hz TBs ($p = .001$), which were also larger than NB CE-Chirps and TBs at 1000 Hz ($p = .022$, $p < .001$, respectively). Besides, n1 and p1 latencies were shorter in NB CE-Chirp than in TB at 500 Hz ($p < .001$) and 1000 Hz ($p < .001$). The older the participants, the lower the amplitudes ($p = .021$, $p = .031$) and the longer the n1 ($p = .030$, $p = .025$) and p1 latencies ($p < .001$, $p < .001$) in 500 Hz NB CE-Chirps and 500 Hz TBs. Interaural asymmetry ratios were slightly higher in 500 Hz NB CE-Chirps as compared to 500 Hz TBs ($p = .013$).

Conclusions: NB CE-Chirps at 500 Hz improved the amplitudes of waveforms in oVEMPs. As for TBs with clicks before, enhancing oVEMPs amplitudes is an essential step to distinguish a healthy person from a patient with either utricular or its related pathways disorder and potentially minimize the risk of cochlear damages. Additional studies including a higher number of healthy participants and patients with vestibular disorders are required to confirm this hypothesis. The large interindividual variability of interaural asymmetry ratios in NB CE-Chirp and in TB at 500 Hz could be explained by the selected montage.

Key words: Air conduction, Frequency, Montage, Narrow band CE-Chirp, Ocular vestibular evoked myogenic potential.

Abbreviations: AEP = auditory evoked potential; ASSR = auditory steady state response; cVEMP = cervical vestibular evoked myogenic potential; dB = decibel; df = degrees of freedom; Hz = Hertz; IAAR = inter-aural asymmetry ratio; ISO = International Organization for Standardization; ms = millisecond; μV = microvolt; NB = CE-Chirp narrow band CE-Chirp; oVEMP = ocular vestibular evoked myogenic potential; Q = quartile; SPL = sound pressure level; TB = tone burst; VEMP = vestibular evoked myogenic potential.

INTRODUCTION

Vestibular evoked myogenic potentials (VEMPs) are used for the assessment of the otolithic organs and otolith-mediated pathways in case of vestibular disorders (Colebatch et al. 2016; Murofushi 2016; Rosengren et al. 2019). They are elicited by a short and intense stimulation of the vestibule, either air, bone, or galvanic-conducted (Rosengren et al. 2010, 2019; Colebatch et al. 2016). Cervical VEMPs (cVEMPs) investigate the function of the saccule and the inferior vestibular nerve (Colebatch et al. 1994; Curthoys et al. 2016). The recording of the myogenic response is usually performed on the ipsilateral sternocleidomastoid muscle. The activation of the saccule directly generates an inhibitory reflex of the previously contracted muscle (Rosengren 2015). Ocular VEMPs (oVEMPs) assess the utricle and the superior vestibular nerve (Rosengren et al. 2005). The activated response is evaluated from the contralateral inferior oblique muscle when the individual looks upward (Weber et al. 2012). In practice, obtaining reliable waveforms of potentials is challenging, especially in oVEMPs (Todd et al. 2007; Rosengren et al. 2019). The identification of peaks depends on numerous individual and material factors like stimulation frequency (Rosengren et al. 2010, 2019; Colebatch et al. 2016; Fife et al. 2017). Although international recommendations about the proper clinical applications of cVEMPs were published (Papathanasiou et al. 2014), there is no clear consensus on how to perform oVEMPs and how they could be further improved. Indeed, the response amplitudes generated by oVEMPs can be very small and gradually decrease with age, mainly in air conduction (Todd et al. 2007).

Tone bursts (TBs) are standard narrow band frequencies stimuli used to produce cVEMPs and oVEMPs (Colebatch et al. 2016; Rosengren et al. 2019). Narrow band CE-Chirps (NB CE-Chirps) are other limited frequency range stimuli that can be used to deliver brief and loud sounds (Rodrigues et al. 2013; Interacoustics 2019). They are increasingly used to obtain auditory steady state responses (ASSRs) in newborns because of their greater frequency specificity compared with TBs (Johnson & Brown 2005; Harte et al. 2007; Ferm et al. 2013, 2015). Given this frequency advantage, we hypothesize that NB CE-Chirps could induce better myogenic reflexes than TBs. Although very few studies have assessed cVEMPs and oVEMPs responses with other kinds of NB Chirps and have provided contradictory results regarding their advantages for optimizing the amplitudes (Özgür et al. 2015; Walther & Cebula 2016; Cebulla & Walther 2019), NB CE-Chirps have never been tested in oVEMPs to our knowledge. To optimize the collection of oVEMPs, we decided to compare these two stimuli (TB versus NB CE-Chirp) at the frequency of 500 Hz and 1000 Hz.

MATERIALS AND METHODS

Subjects

A group of 21 healthy volunteers with no otologic or neurological disorder were included in this prospective study (12 men, 9 women; mean ± SD = 36.43 ± 13.07 years, range = 21 to 67 years).

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TABLE 1. Exclusion criteria

Exclusion criteria	Definition of the criteria
Conductive or mixed hearing loss	Rinne strictly higher than 10 dB on one of the tested frequencies
Suspicion of retrocochlear pathology	Discrepancy between speech audiometry and pure-tone audiometry
Asymmetric neurosensory hearing loss	Asymmetry higher than 15 dB in comparison with the average frequencies 500–1000–2000 and 4000 Hz (Vannson et al. 2015)
Previous otologic problems	
Previous balance problems	
Previous oculomotor problems	
Neurological or muscular pathology that can alter myogenic responses	
Diabetes	
Taking ototoxic or myorelaxant medication	

dB, decibel; Hz, Hertz.

A selective questionnaire was completed with the volunteers to identify exclusion criteria (Table 1). A series of pretests, whose calibration was checked before the start of the study, was also conducted: micro-otoscopy (Zeiss OPMI Pico, Germany), tympanometry at 226 Hz (GSI TympStar Grason-Stadler, Eden Prairie, MN, USA), air and bone-conducted pure-tone liminar audiometry with a TDH 39 headphone and B71 bone vibrator (Equinox; Interacoustics, Middelfart, Denmark), and speech audiometry with french Fournier's disyllabic word lists (Equinox; Interacoustics, Middelfart, Denmark). The last two exams were performed in a sound-treated audiometric test booth (Boët StopSon, Villeneuve-d'Ascq, France).

Recording Procedure of oVEMPs

Participants were seated in a height-adjustable chair in a soundproof and faradized booth (BERA; Boët StopSon, Villeneuve-d'Ascq, France). While releasing tension in the face, they were instructed to maintain focus on a bright red target on the opposite wall, 2 meters away to prevent accommodation during the recording procedure. The visual target formed an upward angle of 30 degrees with a horizontal plane corresponding to the rest position of the eyes. The option to adjust the height of the chair makes it possible to maintain the angle constant despite the different sizes of the individuals. To prevent the volunteer from raising their heads during the test, a chinstrap was used. A "belly-tendon" electrode montage was applied to record the myogenic response (Fig. 1) (Sandhu et al. 2013). Skin was prepared (Nuprep Skin Prep Gel; Weaver and Company, Colorado, USA and Ether). The active electrode (133 Foam Electrodes; Covidien, Massachusetts, USA) was placed 1 cm under the free edge of the inferior eyelid contralateral to the stimulation, slightly shifted outward when compared with the middle of the eye. In this way, the electrode was placed close to the inferior oblique muscle on the skin. The reference electrode was placed in the internal canthus contralateral to the stimulation. The ground electrode was placed on the forehead. The electrode impedance was kept below 5 kΩ and the inter-electrode impedance was below 3 kΩ. Insert earphones (INSERT 3M E-A-RTONE 3A, Minneapolis, USA) were put in each ear. The recording of the myogenic response and the sound delivery were carried out using the Eclipse EP25 module (Interacoustics, Assens, Denmark) according to a proper calibration based on the International Organization for Standardization ISO 389-6. Each ear was tested separately via air-conducted sound for recording contralateral myogenic responses. For each ear, sound stimuli generated were TB and

NB CE-Chirp at the intensity level of 100 dB nHL. Frequencies of 500 Hz and 1000 Hz were used for each of the stimuli. Peak SPLs were 123.5 dB peak SPL for TB 500 Hz, 125.5 dB peak SPL for NB CE-Chirp 500 Hz, 121.5 dB peak SPL for TB 1000 Hz, and 124 dB peak SPL for NB CE-Chirp 1000 Hz. Each TB was delivered for 6 ms (2–2–2 ms rise, fall, and plateau time, respectively) and repeated 100 times for one acquisition. For TBs 500 Hz and 1000 Hz, frequency spectrums are in line with the International Electrotechnical Commission IEC 60645-3. NB CE-Chirps lengths were predefined from 4.5 ms for 500 Hz (range 360 to 720 Hz) to 3.5 ms for 1000 Hz (range 720 to 1440 Hz) (Interacoustics 2019). They were also repeated 100 times for one acquisition. Based on the optimal parameters reported in the literature (Rosengren et al. 2010, 2019; Colebatch et al. 2016), a repetition rate of 5.1/s with a rarefaction polarity and a band-pass filter of 1 to 1000 Hz were selected. Electrical activity was recorded from 20 ms before to 80 ms following stimulus onset. For each participant, the initial laterality as well as the order of the individual tests were also randomized. The variables
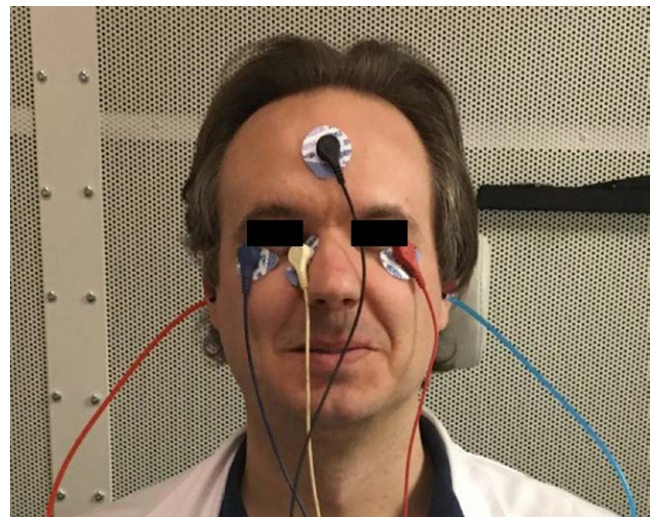

Fig. 1. "Belly-tendon" montage. The red and blue electrodes positioned in front of the inferior oblique muscle correspond to the active electrodes (red for the right ear and blue for the left ear). The beige electrode placed in the internal canthus contralateral to the stimulation corresponds to the reference electrode. The reference electrode is placed on the right internal canthus for assessing the left utricle and its afferents. This electrode is moved on the left internal canthus when the right utricle is evaluated. The ground electrode (black) is placed on the forehead. Insert earphones are inserted in the external auditory canals (red for the right ear and blue for the left ear).
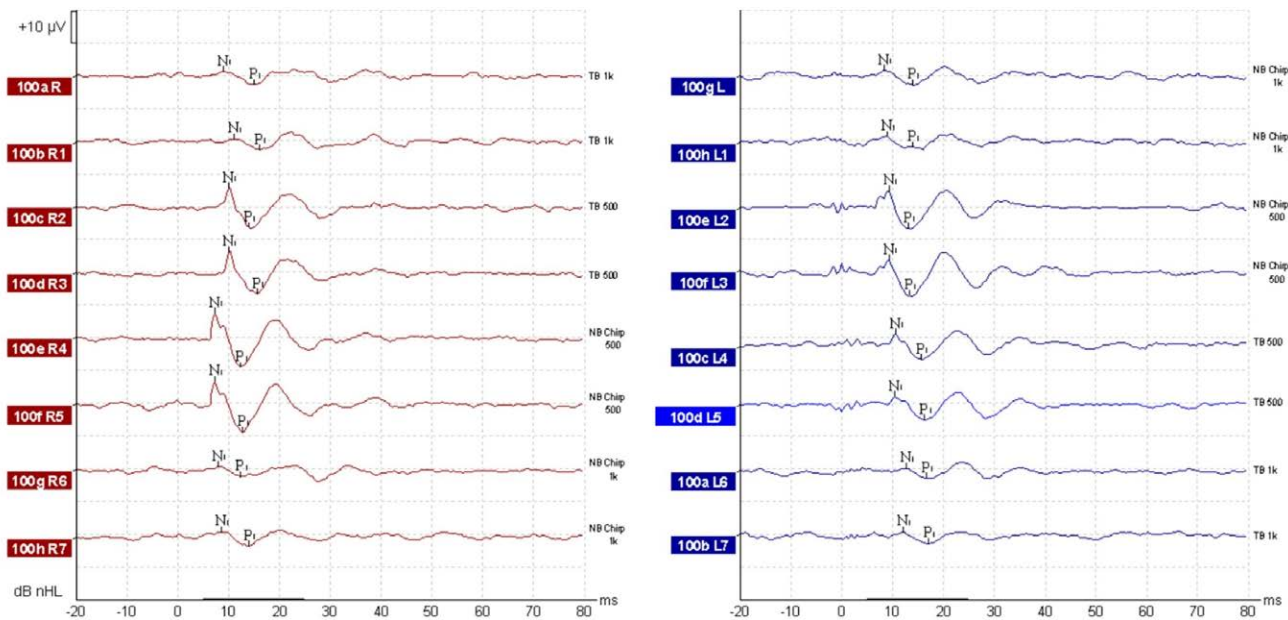
Fig. 2. Example of oVEMP waveforms recorded in a healthy volunteer. Waveforms recorded for the right ear (red) and the left ear (blue) according to the stimulus (TB vs. NB CE-Chirp) and the frequency (500 vs. 1000 Hz). NB CE-Chirp indicates Narrow band CE-Chirp; oVEMP, ocular vestibular evoked myogenic potential; TB, tone burst.

of interest were the peak to peak amplitudes n1-p1 (µV) and the latency n1 and p1 (ms) (Fig. 2). Interaural asymmetry ratios (IAARs) were computed using the following formula: IAAR (%) = 100 × (biggest amplitude [µV]–smallest amplitude [µV])/ (biggest amplitude [µV] + smallest amplitude [µV]) (Jongkees et al. 1962). To assess the reproducibility of data, each recording procedure was repeated twice and averaged. The participant was granted 1 minute's rest between each recording.

Statistical Analysis

We analyzed the peak to peak amplitudes n1-p1, the n1 and p1 latencies, and the IAARs. Continuous variables were described using means and SDs or medians and interquartile ranges according to the normality of parent distributions. Normality was assessed using QQ plots and Shapiro-Wilk tests. Comparisons between right and left ears of the same individual were performed using Wilcoxon signed-rank tests. Continuous variables were compared using nonparametric procedures for paired data (Friedman tests and Wilcoxon signed-rank tests), with Dunn-Bonferroni procedures for post hoc multiple comparisons. Correlation analyses were performed using Pearson or Spearman correlation coefficients as appropriate, with the use of logarithmic transformations if required. All tests were two-sided with an alpha error level at 0.05. A $p < 0.05$ was considered significant. Statistical analyses were conducted using the software IBM SPSS Statistics version 23.0 (IBM, Ehningen, Germany).

Ethics Approval Statement

Approval for any experiments was obtained from the institutional ethics committee (CCB: B325201939623) and written informed consent was obtained from all participants for this study. Written informed consent was obtained from the individual for the publication of any potentially identifiable images or data included in this article.

RESULTS

In 100% of cases, oVEMPs were detected bilaterally in TB and NB CE-Chirp with a frequency of 500 Hz. Ninety-five percent of the participants showed bilateral oVEMPs in TB and NB CE-Chirp with the frequency of 1000 Hz. Only one 38-year-old man did not show oVEMP responses bilaterally for TBs and NB CE-Chirps at 1000 Hz.

There were no differences for the studied parameters (amplitudes n1-p1, n1 and p1 latencies) between the right and the left ears (T = 1363 [$Z = −1.23$], $p = .218$; T = 1428 [$Z = −.18$], $p = .856$; T = 1342 [$Z = −.44$], $p = .661$, respectively; Wilcoxon signed-rank test). Consequently, the data obtained by both ears were pooled.

The comparison of the amplitudes according to the stimulus and the frequency showed significant differences (χ^2 [3 degrees of freedom] = 80.44, $p < .001$, Friedman test) with bigger amplitudes in 500 Hz NB CE-Chirp (median = 20.43 µV, Q1 = 12.53 µV, Q3 = 31.04 µV) than in 500 Hz TB (median = 15.81 µV, Q1 = 9.17 µV, Q3 = 27.36 µV) ($p = .001$, Dunn-Bonferroni). The amplitudes obtained in 500 Hz TB were larger than in NB CE-Chirp 1000 Hz (median = 8.37 µV, Q1 = 3.87 µV, Q3 = 22.09 µV) ($p = .022$, Dunn-Bonferroni) and TB 1000 Hz (median = 7.33 µV, Q1 = 4.28 µV, Q3 = 19.25 µV) ($p < .001$, Dunn-Bonferroni). There was no significant difference between the amplitude values obtained in TB and NB CE-Chirp with the frequency of 1000 Hz ($p = .5$, Dunn-Bonferroni) (Fig. 3).

N1 latencies were shorter in NB CE-Chirp 500 Hz (median = 7.17 µV, Q1 = 7 µV, Q3 = 7.96 µV) than in TB 500 Hz (median = 10 µV, Q1 = 9.67 µV, Q3 = 10.5 µV) ($p < .001$, Dunn-Bonferroni). Similarly, n1 latencies were shortened in NB CE-Chirp (median = 7.84 µV, Q1 = 7.5 µV, Q3 = 8.17 µV) in comparison with TB (median = 9.84 µV, Q1 = 9.54 µV, Q3 = 10.34 µV) at 1000 Hz frequency (p < .001, Dunn-Bonferroni) (Fig. 4A). As for p1 latencies, there was also a difference depending on the stimulus and its frequency (χ^2 [3 degrees of freedom] = 100.97, $p < .001$, Friedman
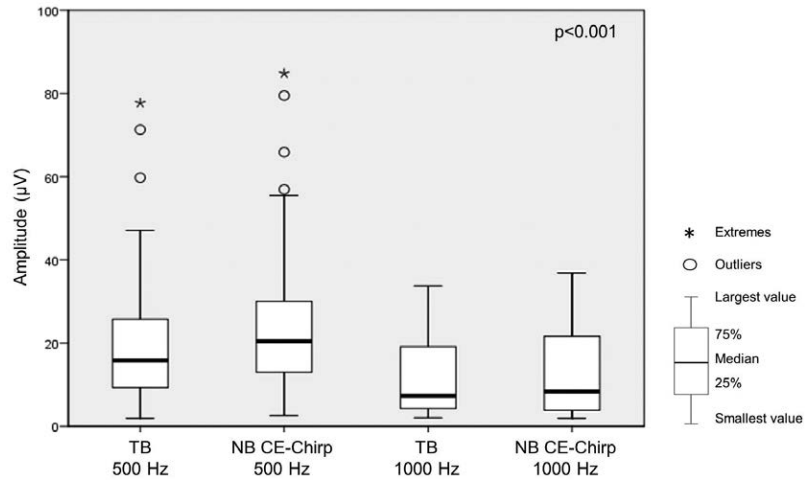
Fig. 3. Boxplots of peak to peak amplitudes. Peak to peak amplitudes (μV) obtained by sound stimulus (TB vs. NB CE-Chirp) and frequency (500 vs. 1000 Hz) used for oVEMPs. Data are presented as boxplots indicating the first and the third quartiles centered on medians (thick lines) with whiskers for the minimum and maximum nonoutlier values, o are outliers, and * show the extreme values. Hz indicates Hertz; NB CE-Chirp, Narrow band CE-Chirp; oVEMP, ocular vestibular evoked myogenic potential; TB, tone burst; μV, microvolts.
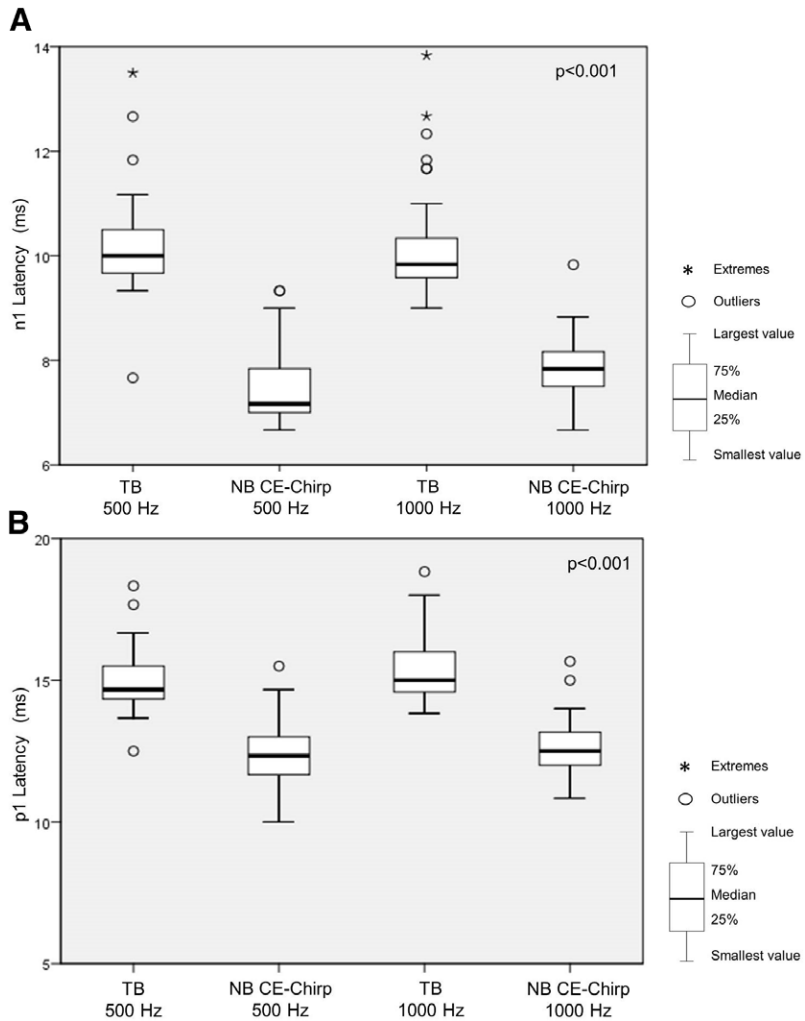
Fig. 4. Boxplots of n1 latency and p1 latency. N1 latency (A) and p1 latency (B) (ms) obtained by sound stimulus (TB vs. NB CE-Chirp) and frequency (500 vs. 1000 Hz) used for oVEMPs. Data are presented as boxplots indicating the first and the third quartiles centered on medians (thick lines) with whiskers for the minimum and maximum nonoutlier values, o are outliers, and * show the extreme values. Hz indicates Hertz; ms, millisecond; NB CE-Chirp, Narrow band CE-Chirp; oVEMP, ocular vestibular evoked myogenic potential; TB, tone burst.
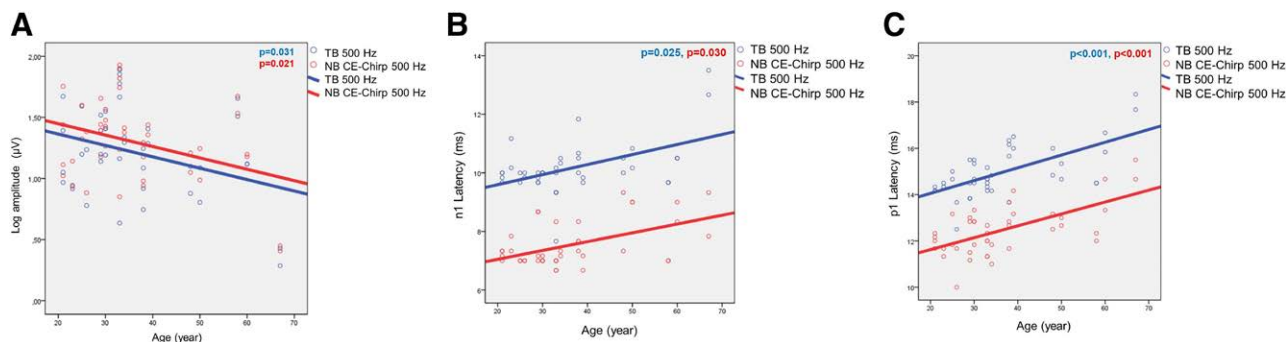
Fig. 5. Correlation between the age and the amplitude logarithm, the n1 and p1 latencies. Scatter plot of Pearson correlation (A) and Spearman correlation (B and C) coefficient between the age (year) and the amplitude logarithm (μV) (A), the n1 (B), and p1 (C) latency (ms) in TB 500 Hz (blue slope) and NB CE-Chirp 500 Hz (red slope) for oVEMPs. Hz indicates Hertz; ms, millisecond; NB CE-Chirp, Narrow band CE-Chirp; oVEMP, ocular vestibular evoked myogenic potential; TB, tone burst; μV, microvolts.

test). Figure 4B shows decreased p1 latencies in NB CE-Chirp at a 500 and 1000 Hz frequency (median = 12.33 μV, Q1 = 11.67 μV, Q3 = 13.04 μV; median = 12.5 μV, Q1 = 12 μV, Q3 = 13.17 μV, respectively) in comparison with TBs 500 and 1000 Hz (median = 14.67 μV, Q1 = 14.29 μV, Q3 = 15.54 μV; median = 15 μV, Q1 = 14.54 μV, Q3 = 16.08 μV, respectively) ($p < .001$, Dunn-Bonferroni).

The logarithm of the peak to peak amplitudes correlated negatively with of age in 500 Hz TB and 500 Hz NB CE-Chirp ($r = -.333$, $p = .031$ and $r = -.356$, $p = .021$, respectively, Pearson correlation test) (Fig. 5A). Simple regression analyses showed increased n1 latencies with the age of the study volunteers in 500 Hz TB and 500 Hz NB CE-Chirp ($\rho = .345$, $p = .025$ and $\rho = .336$, $p = .030$, respectively, Spearman rank correlation coefficient) (Fig. 5B). Regarding p1 latencies, the same profile of correlation as for n1 latencies in 500 Hz TB and 500 Hz NB CE-Chirp was observed ($\rho = .615$, $p < .001$ and $\rho = .516$, $p < .001$, respectively, Spearman rank correlation coefficient) (Fig. 5C).

Finally, we found that the values of IAARs were slightly higher in 500 Hz NB CE-Chirps than in 500 Hz TBs (T = 253 [$Z = -2.48$], $p = .013$; effect size = .54, Wilcoxon signed-rank test). A median value of 22.28% (Q1 = 7.89%, Q3 = 31.25%) for NB CE-Chirps 500 Hz and of 19.04% (Q1 = 8.33%, Q3 = 36.22%) for TBs 500 Hz was observed (Fig. 6). Nevertheless,

a large interindividual dispersion was obvious whatever the selected stimulation procedure. The 95th percentile IAAR was 50.3% for NB CE-Chirps 500 Hz and 53.9% for TBs 500 Hz.

DISCUSSION

The type of stimulus used is one of the key parameters, which influences the n1-p1 amplitudes of VEMPs (Rosengren et al. 2009). Due to their common use in the auditory evoked potentials (AEPs), click stimuli were first described (Colebatch et al. 1994). They are characterized by a short-length stimulation (usually 0.1 ms) and a large frequency range (Elberling et al. 2007). TB delivered at a frequency of 500 Hz has eventually been accepted as the standard stimulus for VEMPs. Indeed, it generates larger amplitudes and better myogenic response rates, mostly due to its better frequency selectivity and longer duration (Chihara et al. 2007; Rosengren et al. 2009, 2011; Viciana & Lopez-Escamez 2012). A frequency tuning to 1000 Hz was also described for older people (Piker et al. 2013). CE-Chirp is an acoustic broadband stimulus whose frequency varies with time and whose use gradually increases in the AEPs (Cebulla et al. 2007; Elberling et al. 2007). Recently, this stimulus has been assessed in cVEMPs and compared with TBs at the frequency of 500 and 1000 Hz. The larger amplitudes were obtained for
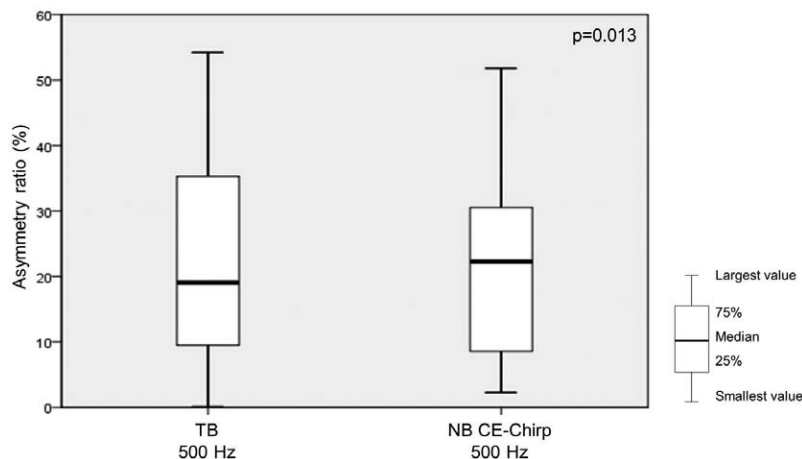

Fig. 6. Boxplots of interaural asymmetry ratios. Interaural asymmetry ratios (%) obtained in TB 500 Hz and NB CE-Chirp 500 Hz for oVEMPs. Data are presented as boxplots indicating the first and the third quartiles centered on medians (thick lines) with whiskers for the minimum and maximum nonoutlier values. % indicates percentage; Hz, Hertz; NB CE-Chirp, Narrow band CE-Chirp; oVEMP, ocular vestibular evoked myogenic potential; TB, tone burst.

TBs 500 Hz (Murofushi et al. 2020). NB CE-Chirps have been designed to obtain ASSRs (Ferm et al. 2013; Rodrigues et al. 2013). Due to their frequency selectivity, the NB CE-Chirps could be adapted to induce oVEMPs.

In our study, the n1-p1 amplitudes were significantly larger when the frequency stimulation was around 500 Hz in TB and in NB CE-Chirp compared with the 1000 Hz frequency. This might be explained by the resonance frequency of the middle ear-vestibular system, which is also around 500 Hz in a healthy young or middle-aged individual (Park et al. 2010; Papathanasiou et al. 2014; Singh & Barman 2014; Colebatch et al. 2016). The best responses obtained at a 500 Hz frequency are in agreement with previous studies (Park et al. 2010; Singh & Barman 2014; Colebatch et al. 2016). It is interesting that the largest amplitudes were obtained when the stimulation was delivered from 500 Hz NB CE-Chirp. Indeed, frequency selectivity is one of the elements that best optimizes the recording of VEMPs (Rosengren et al. 2009). Like NB CE-Chirps, TBs are short-length stimuli with a narrow range of frequency (Elberling et al. 2007). Nevertheless, it has been demonstrated in ASSRs that TBs elicited smaller wave V amplitudes than NB CE-Chirps because the frequency selectivity of TBs is partly altered by a phenomenon of spectral splatter (Johnson & Brown 2005; Harte et al. 2007; Ferm et al. 2013, 2015). Indeed, the frequency spectrum of TBs shows a main wave of energy and side waves of energy at lower and higher frequencies (Harte et al. 2007; Johnson & Brown 2005). These side waves are not present for NB CE-Chirps and allow better frequency selectivity. It could explain the amplitudes differences observed in our study at 500 Hz. There are very few studies that have investigated other kinds of narrow band Chirps in VEMPs with conflicting results regarding their advantages for optimizing the amplitudes. A first study compared the amplitudes obtained in oVEMPs and cVEMPs when the stimulus was a click, a TB 500 Hz, or a Cebulla Walther-VEMP-Chirp that is a narrow band chirp especially designed for VEMPs with a frequency range of 250 to 1000 Hz in air conduction (Walther & Cebulla 2016). The highest amplitudes were observed in Cebulla Walther-VEMP-Chirp, which agrees with our results. A second study also compared the responses obtained with these same types of stimuli when recording air-conducted cVEMPs (Özgür et al. 2015). In this case, the NB Chirps revealed the lowest amplitudes. The large range of frequency of these NB Chirps (500 to 4000 Hz) as well as the position of the stimulus (not quite centered on 500 Hz frequency) might explain these results. These observations highlight the great importance of using a stimulus of a narrow range of frequency, centered on 500 Hz without spectral splatter phenomenon as for NB CE-Chirps (range 360 to 720 Hz) used in our study. It would be interesting to whether such a stimulus might differentiate more precisely a falsely absent response to a patient with an utricular disorder. Furthermore, optimizing oVEMPs amplitudes would allow us to reduce sound intensity required to elicit oVEMPs and thus minimize the risk of cochlear damages when performing the test.

Regarding n1 and p1 latencies, they were significantly shorter in NB CE-Chirp whatever the frequency. It has been shown that n1 and p1 latencies are significantly longer when the stimulus delivered is a TB in comparison with a click (Chihara et al. 2007; Kumar et al. 2011). The difference in the rise time of a stimulus is one of the major factors influencing the VEMPs latencies (Burgess et al. 2013; Kantner et al. 2014). As clicks

have far shorter rise time than TBs, VEMPs latencies are shortened for clicks. In our study, shorter rise time for NB CE-Chirps might justify shorter latencies (Ferm et al. 2013). Besides, it has been suggested that primary vestibular neurons may have double or triple firing to one TB and the latencies of VEMPs responses might be delayed due to the second or third spikes, unlike NB CE-Chirps (Cheng & Murofushi 2001). Finally, the presentation time of NB CE-Chirps is always earlier than for TBs. As for AEPs, this could explain the latencies differences observed (Ferm et al. 2013).

Regarding the age of the study participants, there was a correlation between amplitudes and n1 and p1 latencies whatever the 500 Hz delivered stimulus (TB versus NB CE-Chirp). No correlation test at 1000 Hz has been carried out because the amplitudes that have been obtained were much better at a 500 Hz frequency. The older the participants, the lower the amplitudes and the higher the n1 and p1 latencies. As described by some authors, degeneration of terminal vestibular organs and their afferencies is the underlying phenomenon (Welgampola & Colebatch 2001; Walther & Westhofen 2007; Tseng et al. 2010; Rosengren et al. 2011; Chang et al. 2012). The age-related variability in the results is usually more obvious in air conduction, but it has also been demonstrated when bone-conducted (Rosengren et al. 2011; Colebatch et al. 2013). As a consequence, a decrease of the percentage of responses obtained over 60 years old is observed, and most authors record rates of oVEMPs responses around 60% from this age (Tseng et al. 2010; Kumar et al. 2015). In our study, myogenic responses were collected in 100% of the cases in TB and NB CE-Chirp at a 500 Hz frequency. However, these results should be taken carefully owing to the small number of 60-year-olds included in the study (n = 2 [1 man], [1 woman]).

The interindividual dispersion of the values of the IAARs in TB and NB CE-Chirp at 500 Hz was larger than usually reported (Chihara et al. 2007; Iwasaki et al. 2008; Wang et al. 2009; Piker et al. 2011). This difference might be related to the montage of the electrodes. When the reference electrode is moved away from the active electrode by placing it on the internal canthus, as described in the "belly-tendon" montage, the reference contamination significantly decreases (Piker et al. 2011; Sandhu et al. 2013; Leyssens et al. 2017; Makowiec et al. 2017; Vanspauwen et al. 2017). So recording muscular responses with significantly higher amplitudes than with a classical infraorbital montage becomes possible even if the tested muscular selectivity and consequently the purity of the reflex might decrease (Piker et al. 2011; Sandhu et al. 2013; Govender et al. 2016; Makowiec et al. 2017). Furthermore, it has been demonstrated that taking away the reference electrode off the inferior oblique muscle sharply increases the measured amplitude variability, which can modify the IAARs (Zuniga et al. 2014). Nevertheless, some authors did not observe an increase of IAARs with the "belly-tendon" montage (Leyssens et al. 2017; Vanspauwen et al. 2017). So it would be interesting to compare the IAARs obtained with the same recording parameters both in the "belly-tendon" and the infraorbital montages.

CONCLUSIONS

oVEMPs are short latency and low amplitude myogenic reflexes for which obtaining reliable waveforms of potentials remains very challenging. NB CE-Chirp represents a promising

parameter to improve the identification of waveforms in air conduction by increasing the measured amplitudes at the 500 Hz optimal frequency, as a result of a better frequency selectivity of NB CE-Chirps in comparison with TBs. Our study showed a correlation between the n1-p1 amplitudes, latencies, and age of the tested volunteers in TB and NB CE-Chirp at a 500 Hz frequency. The interindividual dispersion of the values of the IAARs in TB and NB CE-Chirp at 500 Hz was higher than what is usually reported. Further studies in a large cohort of healthy subjects and selected patients with a vestibular disorder are warranted.

REFERENCES

Burgess, A. M., Mezey, L. E., Manzari, L., MacDougall, H. G., McGarvie, L. A., Curthoys, I. S. (2013). Effect of stimulus rise-time on the ocular vestibular-evoked myogenic potential to bone-conducted vibration. *Ear Hear*, *34*, 799–805.

Cebulla, M., & Walther, L. E. (2019). Cervical vestibular evoked myogenic potentials via air conduction delivered by either sequentially or quasi-simultaneously presented narrow-band chirp stimuli. *Int J Audiol*, *58*, 174–179.

Cebulla, M., Stürzebecher, E., Elberling, C., Müller, J. (2007). New click-like stimuli for hearing testing. *J Am Acad Audiol*, *18*, 725–738.

Chang, C. M., Young, Y. H., Cheng, P. W. (2012). Age-related changes in ocular vestibular-evoked myogenic potentials via galvanic vestibular stimulation and bone-conducted vibration modes. *Acta Otolaryngol*, *132*, 1295–1300.

Cheng, P. W., & Murofushi, T. (2001). The effects of plateau time on vestibular-evoked myogenic potentials triggered by tone bursts. *Acta Otolaryngol*, *121*, 935–938.

Chihara, Y., Iwasaki, S., Ushio, M., Murofushi, T. (2007). Vestibular-evoked extraocular potentials by air-conducted sound: Another clinical test for vestibular function. *Clin Neurophysiol*, *118*, 2745–2751.

Colebatch, J. G., Govender, S., Rosengren, S. M. (2013). Two distinct patterns of VEMP changes with age. *Clin Neurophysiol*, *124*, 2066–2068.

Colebatch, J. G., Halmagyi, G. M., Skuse, N. F. (1994). Myogenic potentials generated by a click-evoked vestibulocollic reflex. *J Neurol Neurosurg Psychiatry*, *57*, 190–197.

Colebatch, J. G., Rosengren, S. M., Welgampola, M. S. (2016). Vestibular-evoked myogenic potentials. *Handb Clin Neurol*, *137*, 133–155.

Curthoys, I. S., Vulovic, V., Burgess, A. M., Sokolic, L., Goonetilleke, S. C. (2016). The response of guinea pig primary utricular and saccular irregular neurons to bone-conducted vibration (BCV) and air-conducted sound (ACS). *Hear Res*, *331*, 131–143.

Elberling, C., Don, M., Cebulla, M., Stürzebecher, E. (2007). Auditory steady-state responses to chirp stimuli based on cochlear traveling wave delay. *J Acoust Soc Am*, *122*, 2772–2785.

Ferm, I., & Lightfoot, G. (2015). Further comparisons of ABR response amplitudes, test time, and estimation of hearing threshold using frequency-specific chirp and tone pip stimuli in newborns: Findings at 0.5 and 2 kHz. *Int J Audiol*, *54*, 745–750.

Ferm, I., Lightfoot, G., Stevens, J. (2013). Comparison of ABR response amplitude, test time, and estimation of hearing threshold using frequency specific chirp and tone pip stimuli in newborns. *Int J Audiol*, *52*, 419–423.

Fife, T. D., Colebatch, J. G., Kerber, K. A., Brantberg, K., Strupp, M., Lee, H., Walker, M. F., Ashman, E., Fletcher, J., Callaghan, B., Gloss, D. S. II. (2017). Practice guideline: Cervical and ocular vestibular evoked myogenic potential testing: Report of the Guideline Development, Dissemination, and Implementation Subcommittee of the American Academy of Neurology. *Neurology*, *89*, 2288–2296.

Govender, S., Cheng, P. Y., Dennis, D. L., Colebatch, J. G. (2016). Electrode montage and gaze effects on ocular vestibular evoked myogenic potentials (oVEMPs). *Clin Neurophysiol*, *127*, 2846–2854.

Harte, J., Dau, T., Favrot, S., et al. (2007, August 29-31). Auditory brainstem responses elicited by embedded narrowband chirps. Proceedings of the 1st International Symposium on Auditory and Audiological Research (ISAAR 2007), Marienlyst, Helsingør, Denmark *1*, 211–220.

Interacoustics. (2019). Additional Information Eclipse. D-0120572 – B -- 2019/03. 239.

Iwasaki, S., Smulders, Y. E., Burgess, A. M., McGarvie, L. A., Macdougall, H. G., Halmagyi, G. M., Curthoys, I. S. (2008). Ocular vestibular evoked myogenic potentials to bone conducted vibration of the midline forehead at Fz in healthy subjects. *Clin Neurophysiol*, *119*, 2135–2147.

Johnson, T. A., & Brown, C. J. (2005). Threshold prediction using the auditory steady-state response and the tone burst auditory brain stem response: A within-subject comparison. *Ear Hear*, *26*, 559–576.

Jongkees, L. B., Maas, J. P., Philipszoon, A. J. (1962). Clinical nystagmography. A detailed study of electro-nystagmography in 341 patients with vertigo. *Pract Otorhinolaryngol (Basel)*, *24*, 65–93.

Kantner, C., Hapfelmeier, A., Drexl, M., Gürkov, R. (2014). The effects of rise/fall time and plateau time on ocular vestibular evoked myogenic potentials. *Eur Arch Otorhinolaryngol*, *271*, 2401–2407.

Kumar, K., Bhat, J. S., Sequeira, N. M., Bhojwani, K. M. (2015). Ageing effect on air-conducted ocular vestibular evoked myogenic potential. *Audiol Res*, *5*, 121.

Kumar, K., Sinha, S. K., Bharti, A. K., Barman, A. (2011). Comparison of vestibular evoked myogenic potentials elicited by click and short duration tone burst stimuli. *J Laryngol Otol*, *125*, 343–347.

Leyssens, L., Heinze, B., Vinck, B., Van Ombergen, A., Vanspauwen, R., Wuyts, F. L., Maes, L. K. (2017). 'Standard' versus 'nose reference' electrode placement for measuring oVEMPs with air-conducted sound: Test-retest reliability and preliminary patient results. *Clin Neurophysiol*, *128*, 312–322.

Makowiec, K., McCaslin, D. L., Jacobson, G. P., Hatton, K., Lee, J. (2017). Effect of electrode montage and head position on air-conducted ocular vestibular evoked myogenic potential. *Am J Audiol*, *26*, 180–188.

Murofushi, T. (2016). Clinical application of vestibular evoked myogenic potential (VEMP). *Auris Nasus Larynx*, *43*, 367–376.

Murofushi, T., Tsubota, M., Tsuda, Y., Yoshimura, E. (2020). Cervical vestibular evoked myogenic potential with chirp sounds. *J Vestib Res*, *30*, 153–158.

Özgür, A., Çelebi Erdivanlı, Ö., Özergin Coşkun, Z., Terzi, S., Yiğit, E., Demirci, M., Dursun, E. (2015). Comparison of tone burst, click and chirp stimulation in vestibular evoked myogenic potential testing in healthy people. *J Int Adv Otol*, *11*, 33–35.

Papathanasiou, E. S., Murofushi, T., Akin, F. W., Colebatch, J. G. (2014). International guidelines for the clinical application of cervical vestibular evoked myogenic potentials: An expert consensus report. *Clin Neurophysiol*, *125*, 658–666.

Park, H. J., Lee, I. S., Shin, J. E., Lee, Y. J., Park, M. S. (2010). Frequency-tuning characteristics of cervical and ocular vestibular evoked myogenic potentials induced by air-conducted tone bursts. *Clin Neurophysiol*, *121*, 85–89.

Piker, E. G., Jacobson, G. P., Burkard, R. F., McCaslin, D. L., Hood, L. J. (2013). Effects of age on the tuning of the cVEMP and oVEMP. *Ear Hear*, *34*, e65–e73.

Piker, E. G., Jacobson, G. P., McCaslin, D. L., Hood, L. J. (2011). Normal characteristics of the ocular vestibular evoked myogenic potential. *J Am Acad Audiol*, *22*, 222–230.

Rodrigues, G. R., Ramos, N., Lewis, D. R. (2013). Comparing auditory brainstem responses (ABRs) to toneburst and narrow band CE-chirp in young infants. *Int J Pediatr Otorhinolaryngol*, 77, 1555–1560.

Rosengren, S. M. (2015). Effects of muscle contraction on cervical vestibular evoked myogenic potentials in normal subjects. *Clin Neurophysiol*, 126, 2198–2206.

Rosengren, S. M., Colebatch, J. G., Young, A. S., Govender, S., Welgampola, M. S. (2019). Vestibular evoked myogenic potentials in practice: Methods, pitfalls and clinical applications. *Clin Neurophysiol Pract*, 4, 47–68.

Rosengren, S. M., Govender, S., Colebatch, J. G. (2009). The relative effectiveness of different stimulus waveforms in evoking VEMPs: Significance of stimulus energy and frequency. *J Vestib Res*, 19, 33–40.

Rosengren, S. M., Govender, S., Colebatch, J. G. (2011). Ocular and cervical vestibular evoked myogenic potentials produced by air- and bone-conducted stimuli: Comparative properties and effects of age. *Clin Neurophysiol*, 122, 2282–2289.

Rosengren, S. M., McAngus Todd, N. P., Colebatch, J. G. (2005). Vestibular-evoked extraocular potentials produced by stimulation with bone-conducted sound. *Clin Neurophysiol*, 116, 1938–1948.

Rosengren, S. M., Welgampola, M. S., Colebatch, J. G. (2010). Vestibular evoked myogenic potentials: Past, present and future. *Clin Neurophysiol*, 121, 636–651.

Sandhu, J. S., George, S. R., Rea, P. A. (2013). The effect of electrode positioning on the ocular vestibular evoked myogenic potential to air-conducted sound. *Clin Neurophysiol*, 124, 1232–1236.

Singh, N. K., & Barman, A. (2014). Characterizing the effects of frequency on parameters of short tone-bursts induced ocular vestibular evoked myogenic potentials. *J Indian Speech Language Hearing Assoc*, 28, 1–9.

Todd, N. P., Rosengren, S. M., Aw, S. T., Colebatch, J. G. (2007). Ocular vestibular evoked myogenic potentials (OVEMPs) produced by air- and bone-conducted sound. *Clin Neurophysiol*, 118, 381–390.

Tseng, C. L., Chou, C. H., Young, Y. H. (2010). Aging effect on the ocular vestibular-evoked myogenic potentials. *Otol Neurotol*, 31, 959–963.

Vannson, N., James, C., Fraysse, B., Strelnikov, K., Barone, P., Deguine, O., Marx, M. (2015). Quality of life and auditory performance in adults with asymmetric hearing loss. *Audiol Neurootol*, 20(Suppl 1), 38–43.

Vanspauwen, R., Wuyts, F. L., Krijger, S., Maes, L. K. (2017). Comparison of different electrode configurations for the oVEMP with bone-conducted vibration. *Ear Hear*, 38, 205–211.

Viciana, D., & Lopez-Escamez, J. A. (2012). Short tone bursts are better than clicks for cervical vestibular-evoked myogenic potentials in clinical practice. *Eur Arch Otorhinolaryngol*, 269, 1857–1863.

Walther, L. E., & Cebulla, M. (2016). Band limited chirp stimulation in vestibular evoked myogenic potentials. *Eur Arch Otorhinolaryngol*, 273, 2983–2991.

Walther, L. E., & Westhofen, M. (2007). Presbyvertigo-aging of otoconia and vestibular sensory cells. *J Vestib Res*, 17, 89–92.

Wang, S. J., Jaw, F. S., Young, Y. H. (2009). Ocular vestibular-evoked myogenic potentials elicited from monaural versus binaural acoustic stimulations. *Clin Neurophysiol*, 120, 420–423.

Weber, K. P., Rosengren, S. M., Michels, R., Sturm, V., Straumann, D., Landau, K. (2012). Single motor unit activity in human extraocular muscles during the vestibulo-ocular reflex. *J Physiol*, 590, 3091–3101.

Welgampola, M. S., & Colebatch, J. G. (2001). Vestibulocollic reflexes: Normal values and the effect of age. *Clin Neurophysiol*, 112, 1971–1979.

Zuniga, M. G., Davalos-Bichara, M., Schubert, M. C., Carey, J. P., Janky, K. L. (2014). Optimizing ocular vestibular evoked myogenic potential testing for superior semicircular canal dehiscence syndrome: Electrode placement. *Audiol Neurootol*, 19, 239–247.