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Air-Conducted Vestibular Evoked Myogenic Potential Testing in Children, Adolescents, and Young Adults: Thresholds, Frequency Tuning, and Effects of Sound Exposure

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Abstract

Objectives—Pediatric vestibular evaluations incorporate cervical and ocular vestibular evoked myogenic potential (c- and oVEMP, respectively) testing; however, in children, c- and oVEMP thresholds have been minimally investigated and frequency tuning is unknown. Children are also at risk for unsafe sound exposure secondary to VEMP. While it is unknown if VEMP threshold testing leads to cochlear changes, it is possible that this risk increases due to the increased number of trials needed to obtain a threshold. Obtaining VEMP thresholds at various frequencies in children provides further information for pediatric normative VEMP data. Assessing for cochlear changes following VEMP threshold testing would provide information on the safety of threshold VEMP testing in children. The objectives of this study were to (1) characterize c- and oVEMP thresholds in children, adolescents, and young adults with normal hearing using 500 Hz and 750 Hz tone burst (TB) stimuli, (2) compare frequency tuning of 500 Hz and 750 Hz TB, and (3) assess whether cochlear changes exist following VEMP threshold testing. It is hypothesized that children, adolescents, and young adults would not show age-related changes to the vestibular system. Therefore, reliable VEMP thresholds would be seen below maximum acoustical stimulation levels (e.g., < 125 dB SPL) and frequency tuning will be similar for 500 Hz and 750 Hz TB stimuli.

Design—10 children (age 4 – 9), 10 adolescents (age 10 – 19), and 10 young adults (age 20 – 29) with normal hearing and tympanometry participated. All subjects received c- and oVEMP testing at maximum stimulation and threshold. To address frequency tuning, but not exceed recommended sound exposure allowance, subjects received a 500 Hz TB stimulus in one ear and a 750 Hz TB stimulus in the other ear. Subjects completed tympanometry pre-VEMP, and audiometric threshold testing, distortion product otoacoustic emission (DPOAE) testing, and subjective questionnaire pre- and post-VEMP to study the effect of VEMP exposure on cochlear function for each stimulus frequency.

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Results—(1) cVEMP thresholds were determined for both stimulus frequencies for children (500 Hz= 106 dB SPL; 750 Hz= 106 dB SPL), adolescents (500 Hz= 107.5 dB SPL; 750 Hz= 109.5 dB SPL) and young adults (500 Hz= 111.5 dB SPL; 750 Hz= 112 dB SPL). oVEMP thresholds were also obtained in response to both stimulus frequencies for children (500 Hz= 111.1 dB SPL; 750 Hz= 112.2 dB SPL), adolescents (500 Hz= 112.5 dB SPL; 750 Hz= 114.5 dB SPL) and young adults (500 Hz= 116 dB SPL; 750 Hz= 117 dB SPL). Similar thresholds were found between groups except for children who had significantly lower thresholds compared to adults for cVEMP (500 Hz: $p= 0.002$; 750 Hz: $p= 0.004$) and oVEMP (500 Hz: $p= 0.01$; 750 Hz: $p= 0.02$). Additionally, equivalent ear canal volume (ECV) and VEMP thresholds were linearly correlated. (2) There was no significant effect of stimulus frequency on VEMP response rates, latencies, peak-to-peak amplitudes, or thresholds, suggesting similar frequency tuning for 500 Hz and 750 Hz. (3) There were no significant effects of VEMP threshold testing on cochlear function for either stimulus frequency.

Conclusions—Children, adolescents, and young adults show VEMP thresholds below high stimulation levels and had similar frequency tuning between 500 Hz and 750 Hz. Use of 750 Hz could be regarded as the safer stimuli due to its shorter duration and thus reduced sound exposure. Children with smaller ECV had present responses at maximum stimulation and lower thresholds, suggesting that VEMP testing could be initiated at lower acoustic levels to minimize sound exposure and optimize testing.

INTRODUCTION

Cervical and ocular vestibular evoked myogenic potentials (c- and oVEMP, respectively) are commonly utilized in the pediatric population. Compared to the adult literature, less is known about normative c- and oVEMP thresholds and frequency tuning; additionally, the impact of sound exposure during threshold testing is undetermined in children. While the VEMP response is influenced by stimulus intensity, frequency, and duration, these parameters also impact the total sound pressure level (SPL) delivered to a child's ear during testing when delivered via air-conduction (Thomas et al. 2017; Rodriguez et al. 2018). Further normative VEMP data and safety acoustic testing would guide pediatric VEMP testing practices so that they are both diagnostically and acoustically appropriate.

The VEMP response is a short latency myogenic potential that can be elicited in response to high sound pressure stimulation, often an air-conducted click or low frequency tone burst (TB) (Colebatch & Halmagyi 1992). The cVEMP, an inhibitory response, is measured from the sternocleidomastoid (SCM) muscle during contraction (Colebatch et al. 1994). The cVEMP pathway extends from the saccule to the inferior vestibular nerve, receives vestibulospinal inputs, and travels to the ipsilateral SCM. The cVEMP response provides information about the saccule and inferior vestibular nerve (Colebatch & Halmagyi 1992; Curthoys 2010). The oVEMP, an excitatory response, is obtained from the inferior oblique (extra-ocular) muscle (Todd et al. 2007). The pathway of the oVEMP response extends from the utricle to the superior vestibular nerve and crosses to the contralateral inferior oblique muscle. As such, the oVEMP predominately evaluates the utricle and superior vestibular nerve; however, the saccule may also contribute to the oVEMP response (Curthoys et al. 2011; Weber et al. 2012).

Performing VEMP testing in the pediatric population is valuable given the otolith organs' contribution to gross motor development and postural control. The vestibulocollic reflex (VCR), with input from the saccule contributes to proper head control (Inoue et al. 2013). Maturation of the translational vestibulo-ocular reflex (VOR) with input from the utricle and saccule, has also been correlated with the development of standing, walking, and postural control in children (Wiener- Vacher et al. 1996; Wang et al. 2013). Conversely, children with impaired saccular and utricular function, meet these gross motor milestones at a later age compared to age-matched peers who do not have vestibular loss (Inoue et al. 2013). In some children, these delays in gross motor development can continue or progress throughout childhood (Rine et al. 2004), which further necessitates reliable measures of vestibular function and subsequent appropriate rehabilitation.

VEMPs can also be reliably tested in children due to early maturation of the VCR and translational VOR (Chen et al. 2007; Chihara et al. 2007; Wang et al. 2008). cVEMP responses can be obtained in full-term newborns as young as 5 days with similar morphology to responses that are elicited in adults (Chen et al. 2007; Wang et al. 2008). However, likely due to variations in neck length, shorter cVEMP p13 and/or n23 latencies have been reported in children compared to adults (Rodriguez et al. 2018) and appear to prolong with age (Kelsch et al. 2006; Maes et al. 2014; Janky & Givens 2015). In contrast, oVEMPs but can be measured in children greater than 12 months of age, with increasing reliability by age 4 years (Wang et al. 2013), with no significant difference in response characteristics from young adults (Hsu et al. 2009; Piker et al. 2011).

Despite the use of VEMP testing in the pediatric population, less is known about normative c- and oVEMP thresholds and frequency tuning curves compared to the adult literature. Results from adult studies consistently demonstrate that c- and oVEMP thresholds increase with age (Janky & Shepard 2009; Piker et al. 2011). Frequency tuning is also most sensitive between 500 Hz and 700–750 Hz for younger to middle- aged adults (Murofushi et al. 1999; Welgampola & Colebatch 2001; Akin et al. 2003; Rauch et al. 2004; Janky & Shepard 2009; Piker et al. 2013). Children (ages 4–15) with normal hearing show similar response rates and c- and oVEMP amplitude responses to that of young adults at high stimulation levels using a 500 Hz TB (Janky & Givens 2015; Rodriguez et al. 2018). cVEMP thresholds in small cohorts of children with normal hearing have been documented in response to 500 Hz (Zhou et al. 2009; Maes et al. 2014; Xu et al. 2015). Piker et al. (2011) and Xu et al. (2015) also reported oVEMP thresholds at 500 Hz in a sub-group of healthy children. Aside, to our knowledge, normative c-and oVEMP threshold data at 750 Hz and frequency tuning between 500 Hz and 750 Hz TB have not been reported in children and adolescents. There is clinical relevance in determining both c- and oVEMP thresholds in children. As reported by Zhou et al. 2011, enlarged vestibular aqueduct (EVA) is the most common inner ear abnormality in children with hearing loss. Diagnostic VEMP indications in EVA are large cVEMP and/or oVEMP amplitudes and low thresholds (Zhou et al. 2011; Taylor et al. 2012). In these instances, both c- and oVEMP threshold normative data could be useful to the pediatric population

However, one risk in completing air-conduction VEMP threshold testing in children and adolescents is the increased sound exposure due to the number of trials required to obtain a

response. Acoustic trauma secondary to VEMP testing has been observed in adults (Krause et al. 2013; Mattingly et al. 2015; Stromberg et al. 2016) in the form of decreased audiometric thresholds, distortion product otoacoustic emission (DPOAE) amplitudes, and subjective symptoms. Therefore, in the context of VEMP testing, stimulus intensity, duration, rise/fall and plateau time should be considered when performing air-conducted VEMPs to minimize sound exposure, as these parameters will affect total sound energy exposure that a person will receive (Colebatch & Rosengren 2014; Singh & Apeksha 2014).

For VEMP exposure, the following sound energy exposure calculation is recommended (ANSI 2013): Stimulus Level (in SPL) – 3dB filter + $10 \times \log_{10}$ (stimulus duration in seconds), with 132 dB SPL as the maximum allowance of exposure according guidelines from the European Union (2003). Children receive approximately 3 dB higher peak equivalent sound pressure level (peSPL) in the ear compared to adults in response to standard VEMP stimuli due to their smaller equivalent ear canal volumes (ECV), and thus are at risk for exceeding the maximum allowance of sound energy exposure following two trials of c- and oVEMP testing, particularly when their ECV is < 0.8 mL (see Table 2 in Rodriguez et al. 2018). Therefore, adding 3 dB to this equation when calculating sound exposure in children is recommended (Rodriguez et al. 2018). Additionally, in children with ECV < 0.8 mL, a 120 dB SPL stimulus intensity is recommended for VEMP testing, which results in reliable VEMP responses without cochlear changes (Rodriguez et al. 2018). Despite these modifications, when considering VEMP threshold testing, the additional number of trials required to obtain a VEMP threshold could further increase the risk of acoustic trauma in children.

One potential solution to minimize acoustic trauma during air-conduction VEMP testing is to use a 750 Hz TB, which has a shorter duration and equates to less sound exposure. It is hypothesized that children, adolescents, and young adults with normal hearing would not show age-related changes and higher frequency tuning curves as seen in older adults. Therefore, VEMP thresholds would be present at lower acoustical stimulation levels and similar frequency tuning to 500 Hz and 750 Hz would occur. Additionally, it is anticipated that by following the recommended allowance for safe sound exposure level (< 132 dB SPL; EU 2003) and accounting for equivalent ECV, cochlear changes would be avoided post c- and oVEMP threshold testing. If these hypotheses hold true, 750 Hz may be the stimulus of choice when testing individuals with smaller equivalent ECV due to its shorter duration and lower sound exposure.

For children, the VEMP test provides a unique contribution to the vestibular battery in that it is an ear- specific, non-invasive tool with high diagnostic capacity to detect otolith loss when age-appropriate normative data is considered. However, there are few investigations characterizing normative air-conducted c- and oVEMP thresholds in children. Additionally, frequency tuning between a 500 Hz and 750 Hz TB stimulus and the impact of sound exposure during threshold VEMP testing in the pediatric population is unknown. Obtaining normative threshold values, frequency tuning data, and determining the impact of sound exposure when performing threshold VEMP can be used to optimize testing techniques in children and adolescents. Therefore, the purpose of the present study was to: (1) characterize c- and oVEMP thresholds in children (4–9 years), adolescents (10–19 years) and young

adults (20–29 years) using 500 Hz and 750 Hz TB stimuli, (2) compare frequency tuning of 500 Hz and 750 Hz, and (3) assess cochlear changes following c- and oVEMP threshold testing as evaluated by audiometric thresholds, DPOAE amplitude, and subjective auditory symptoms.

METHODS AND MATERIALS

Study Population

Ten children (mean age 6.5 years; range 4–9 years; 5 males) and 10 adolescents (mean age 13.6 years; range 10–19 years; 3 males) with normal hearing and tympanometry participated in this study. Ten young adults with normal hearing (mean age 25.7 years; range 21–29 years; 3 males) also participated. For all subjects, diagnostic tympanometry (GSI Tympanstar, Grason-Stradler, Eden Prairie, MN, USA) using a 226 Hz probe tone was performed in both ears to record the equivalent ECV and verify tympanic membrane motility prior to VEMP testing. Tympanometry was considered normal if peak admittance was < 0.3 mmhos and peak pressure was between -100 and 30 daPa. Participants with a history of hearing loss, otologic surgery, balance/dizziness symptoms, neurological disorders, or abnormal results on tympanometry were excluded from this study and further VEMP testing was not performed. Informed consent was obtained from all subjects for testing approved by the Institutional Review Board at Boys Town National Research Hospital.

Cervical and Ocular VEMP Measurements

To address the gaps in the literature regarding frequency tuning and the impact of unsafe sound exposure secondary to air-conduction VEMP threshold testing in children, a 500 Hz and 750 Hz TB air-conducted stimulus was utilized for all VEMP testing. To compare VEMP responses between 500 Hz and 750 Hz, each subject was randomly assigned one ear to receive a 500 Hz TB while the other ear received a 750 Hz TB. VEMP measurements were obtained using an ICS Chartr 200 Evoked Potential System (GN Otometrics, Taastrup, DK) and stimuli were delivered via ER-3A insert earphones. Stimuli used were 500 Hz (4 ms total duration) and 750 Hz (2.67 ms total duration) rarefaction TB at a repetition of rate of 5.1 per second (Blackman gating window, 1 cycle rise/fall time, 0 cycle plateau). A band-pass filter of 10–1000 Hz (cVEMP) and 2–500 Hz (oVEMP) was utilized.

As shown in Figure 3A, the electrode montage for cVEMP testing included an active electrode placed on the belly of the sternocleidomastoid (SCM) muscle, an electromyography (EMG) monitoring electrode directly below the SCM electrode, a ground electrode on the chin, and a reference electrode on the manubrium of the sternum. As shown in Figure 3B, the electrode montage used for oVEMP testing included an active electrode under the contralateral eye placed over the belly tendon of the inferior oblique muscle, which lies medio-lateral to the infraorbital midline as recommended by Sandhu et al. (2013). A ground electrode was placed on the manubrium of the sternum and reference electrode on the chin. A chin reference was selected to minimize amplitude reduction secondary to recording contamination which can occur from close proximity of the active and reference electrodes (Piker et al. 2011; Zuniga et al. 2014). Throughout c- and oVEMP testing subjects were in a supine position, with the head elevated at ~ 45 degrees. For cVEMP, subjects were

instructed to turn their head away from the ear being stimulated and lift their head up in response to acoustic stimulation. One hundred sweeps were averaged for each cVEMP test. EMG activity was recorded for the total stimulation time; however, only the EMG activity that fell within the range of 50–300 (μ V) was included in the averaged cVEMP response (also see Table 1). EMG activity that did not fall within this range was recorded as number of rejected stimuli. Additional cVEMP parameters recorded were p13 and n23 latencies (ms), the p13 to n23 peak-to-peak amplitude (μ V), and average EMG activity for left and right side per trial. The uncorrected peak-to-peak amplitude for cVEMP was calculated as the absolute difference between the p13 and n23 peak. The corrected peak-to-peak amplitude was derived by dividing the uncorrected amplitude by the average EMG level. During oVEMP testing, adults were instructed to focus their gaze on a mark on the ceiling set at 30 degrees up-gaze in response to acoustic stimulation. Children and adolescents were instructed to watch a video playing on an iPod (Apple Inc, Cupertino, CA) attached to the ceiling set at 30 degrees up-gaze. One-hundred and fifty sweeps were averaged for each oVEMP test. oVEMP parameters recorded included n10 and p16 latencies (ms) and the n10 to p16 peak-to-peak amplitude (μ V). The uncorrected peak-to-peak amplitude for oVEMP was calculated as the absolute difference between the n10 and p16 peak.

To confirm a present VEMP response, two trials at maximum stimulation were initially presented at 125 dB SPL in individuals with an equivalent ECV > 0.8 mL and 120 dB SPL if the ECV was ≤ 0.8 mL as recommended by Rodriguez et al. (2018). Thresholds were then determined using a descending method (i.e., down 10 dB, up 5 dB increments) for adults; an ascending method was used for children and adolescents (i.e., starting at 100 dB SPL, down/up by 5 dB increments) to minimize unnecessary sound exposure at higher SPL and optimize testing time in the event the child became fatigued. A threshold was confirmed as the lowest stimulation level that elicited a repeatable c- or oVEMP response, with a no response observed 5 dB below threshold (Jacobson & Shepard 2016).

Otoacoustic Emissions

To measure the effect of VEMP exposure on outer hair cell function, DPOAE measurements were recorded using a Biologic AuDX Pro Diagnostic Otoacoustic Emissions System (Natus Incorporated, San Carlos, CA) with Scout Otoacoustic Emissions software (Version 3.45.00) before (pre-VEMP) and within 10 minutes following (post-VEMP) c- and oVEMP threshold testing. Measurements were taken with the participant sitting in an upright position in a quiet room. The frequency ratio of the stimulus tones was $f_2/f_1 = 1.2$ and the stimulus level pair 65/55 dB SPL was used. For f_2 ; the frequencies 0.75, 1000, 1500, 2000, 3000, 6000, and 8000 Hz were tested.

Similar to the methods used in Rodriguez et al. (2018), 2 DPOAE trials were performed in each left and right ear pre-VEMP, and 1 DPOAE measurement was performed in each ear post-VEMP. DPOAE amplitude differences from pre- to post-testing can be influenced by probe re-insertion (Reavis et al. 2015). To estimate the test-retest variability prior to VEMP exposure, 95% confidence intervals (CI) were calculated using the difference in DPOAE amplitude between the 2 pre-VEMP trials for each frequency tested. The post-OAE value was subtracted from the pre-DPOAE amplitude. If the difference was outside the 95% CI, it

was considered to be a difference attributed to VEMP exposure and not test-retest. To determine a significant change in signal-to-noise ratio DPOAE amplitude related to VEMP testing, the post-VEMP DPOAE amplitude was subtracted from the averaged pre-VEMP DPOAE amplitude. If the value was a negative value (suggesting a decrease in the DPOAE amplitude) and was outside of the 95% CI, a significant DPOAE shift was reported for that frequency in the respective ear.

Audiometric Threshold Testing

To assess the effect of VEMP threshold testing on audiometric thresholds, air-conduction testing was performed using a GSI 61 two-channel diagnostic audiometer (Grason-Stadler, Madison, WI, USA) pre- and post-VEMP testing. Frequencies of 500, 750, 1500, 2000, 3000, 4000, and 6000 Hz were tested in each ear using insert earphones.

Otologic Subjective Symptom Questionnaire

To evaluate if perceptual changes in auditory function followed VEMP threshold exposure, subjects were asked to report subjective symptoms related to their hearing (e.g., aural fullness, otalgia, tinnitus, or decreased hearing sensitivity) using a 4-item questionnaire used in Rodriguez et al. (2018) (see Supplemental Appendix). For each subject, the examiner physically presented the questionnaire and verbally read each question aloud. The examiner recorded the subject's response. If the subject did not respond to the question or had difficulty answering the question, this was noted by the examiner. The questionnaire was completed before and immediately after VEMP testing.

Statistical Analyses

A 2-way analysis of variance (ANOVA) was conducted to determine the effect of stimulus frequency (500 Hz vs 750 Hz) and age group (children vs adolescents vs adults) on VEMP latencies, amplitudes, and thresholds. Repeated measures ANOVA was performed to determine the effect of VEMP threshold exposure (pre-VEMP vs post-VEMP threshold testing) and stimulus frequency (500 Hz and 750 Hz) on audiometric thresholds and DPOAE amplitude in the respective ear.

RESULTS

VEMP Responses in Children, Adolescents, and Young Adults with Normal Hearing in Response to 500 Hz and 750 Hz TB Stimuli

cVEMP Responses—cVEMP response rates were 100% for 500 Hz and 750 Hz TB stimuli in children, adolescents, and adults at maximum stimulation level (e.g., 120 for ECV 0.8 mL; 125 dB SPL for ECV > 0.8 mL). EMG contraction level was not significantly different between groups [$F(2, 27) = 0.12$, $p = 0.89$]. There was also no significant difference between left and right EMG level ($t = 0.87$; $p = 0.93$). Table 1 shows that at maximum stimulation level, there was no main effect of stimulus frequency (500 Hz vs 750 Hz) for p13 latency [$F(1, 54) = 2.03$; $p = 0.16$], n23 latency [$F(1, 54) = 0.60$; $p = 0.44$], or corrected peak-to-peak amplitude [$F(1, 54) = 0.54$; $p = 0.47$]. There was no main effect for age group on cVEMP corrected peak-to-peak amplitude [$F(2, 54) = 3.3$; $p = 0.40$]; however, there was a main effect for age group on p13 latency [$F(2, 54) = 6.22$; $p = 0.004$] and n23

latency [$F(2, 54) = 9.63$; $p < 0.0001$]. Post-hoc analysis revealed that p13/n23 latencies increased as a function of age; adults had significantly longer p13 ($p = 0.009$) and n23 ($p = 0.001$) latencies compared to children. Adolescents also had significantly longer p13 ($p = 0.01$) and n23 latencies ($p = 0.004$) compared to children. There were no cVEMP latency differences between adults and adolescents ($p = 0.34$). No significant interaction between stimulus frequency and age group was observed for p13 [$F(2, 54) = 0.13$; $p = 0.89$], n23 [$F(2, 54) = 0.27$; $p = 0.77$], or corrected peak-to-peak amplitude [$F(2, 54) = 0.15$; $p = 0.87$].

At threshold level (see Table 2), EMG contraction level was not significantly different between groups [$F(2, 27) = 2.66$, $p = 0.88$]. There was also no significant difference between left and right EMG level ($t = 0.98$; $p = 0.35$). ANOVA results also confirmed there was no main effect of stimulus frequency on thresholds [$F(1, 54) = 1.03$; $p = 0.31$]. A main effect of age group on threshold [$F(2, 54) = 36.76$; $p < 0.0001$] was observed, where children (500 Hz = 106 dB SPL, $p = 0.002$; 750 Hz = 106 dB SPL, $p = 0.004$) had lower thresholds compared to adults (500 Hz = 111.5 dB SPL; 750 Hz = 112 dB SPL); however, significance was not found between children and adolescents (500 Hz: $p = 0.10$; 750 Hz: $p = 0.20$) or adults and adolescents (500 Hz: $p = 0.16$; 750 Hz: $p = 0.27$). No significant interaction between stimulus frequency and age group was observed for threshold [$F(2, 54) = 0.32$; $p = 0.73$].

To determine the impact of EMG contraction level on cVEMP amplitudes and thresholds, we assessed the relationship between these factors. A linear relationship between EMG contraction level and uncorrected amplitude was noted at maximum stimulation (500 Hz: $r = 0.50$; $p = 0.005$; 750 Hz: $r = 0.51$; $p = 0.004$) and threshold level (500 Hz: $r = 0.30$; $p = 0.01$; 750 Hz: $r = 0.34$; $p = 0.009$). However, after correcting for the influence of EMG contraction level on cVEMP amplitude, the relationship between EMG level and corrected amplitude at maximum stimulation (500 Hz: $r = 0.09$, $p = 0.63$; 750 Hz: $r = 0.08$, $p = 0.66$) and threshold (500 Hz: $r = 0.12$, $p = 0.54$; 750 Hz: $r = 0.24$, $p = 0.23$) was not significant. There was also no significant association between EMG level and cVEMP threshold (500 Hz: $r = 0.09$, $p = 0.64$; 750 Hz: $r = 0.04$, $p = 0.84$).

oVEMP Responses—oVEMP response rates at maximum stimulation level were 100% for all groups for both 500 Hz and 750 Hz TB (refer to Table 1). There was no main effect of stimulus frequency on n10 latency [$F(1, 54) = 0.63$; $p = 0.43$], p16 latency [$F(1, 54) = 0.23$; $p = 0.88$], or peak-to-peak amplitude [$F(1, 54) = 4.00$; $p = 0.08$]. There was no main effect of age group on n10 latency [$F(2, 54) = 0.63$; $p = 0.43$], p16 latency [$F(2, 54) = 0.23$; $p = 0.88$], or peak-to-peak amplitude [$F(2, 54) = 1.42$; $p = 0.17$]. Additionally, no interaction between stimulus frequency and age group was observed for n10 [$F(2, 54) = 2.93$; $p = 0.02$], p16 [$F(2, 54) = 0.76$; $p = 0.66$], or peak-to-peak amplitude [$F(2, 54) = 4.97$; $p = 0.10$].

At threshold level, there was no main effect of stimulus frequency on oVEMP thresholds [$F(1, 54) = 3.4$; $p = 0.07$] (refer to Table 2). A main effect of age group was noted for oVEMP thresholds [$F(2, 54) = 21.84$; $p < 0.0001$]. Post-hoc analysis suggests that adults had significantly higher thresholds (500 Hz = 116 dB SPL, $p = 0.01$; 750 Hz = 117 dB SPL, $p = 0.02$) compared to children (500 Hz = 111.1 dB SPL; 750 Hz = 112.2 dB SPL); however, significance was not found between children and adolescents (500 Hz: $p = 0.21$; 750 Hz: $p =$

0.65) or adults and adolescents (500 Hz: $p=0.18$; 750 Hz: $p=0.32$). No significant interaction between stimulus frequency and age group was observed for thresholds [$F(2, 54) = 0.08$; $p=0.92$].

Relationship between Cervical and Ocular Thresholds, Age, and Equivalent

ECV—To determine the relationship between age and equivalent ECV on VEMP thresholds at 500 and 750 Hz, a regression analysis was performed for both predictors. A positive relationship did exist between age and cVEMP threshold [500 Hz: $R^2 = 0.45$, $F(1, 28) = 23.56$, $p < 0.0001$; 750 Hz: $R^2 = 0.43$, $F(1, 28) = 21.16$, $p < 0.0001$] and oVEMP threshold [500 Hz: $R^2 = 0.54$, $F(1, 28) = 36.51$, $p < 0.0001$; 750 Hz: $R^2 = 0.44$, $F(1, 28) = 66.49$, $p < 0.0001$] (see Figure 1, left). However, a stronger positive linear relationship between ECV and VEMP thresholds was observed comparatively (see Figure 1, right). As ECV size increased, threshold response increased for both cVEMP [500 Hz: $R^2 = 0.64$, $F(1, 28) = 48.85$, $p < 0.0001$; 750 Hz: $R^2 = 0.72$, $F(1, 28) = 72.22$, $p < 0.0001$] and oVEMP [500 Hz: $R^2 = 0.62$, $F(1, 28) = 47.96$, $p < 0.0001$; 750 Hz: $R^2 = 0.52$, $F(1, 28) = 31.87$, $p < 0.0001$]. Analysis of ECV differences between groups showed no difference between children ($M = 0.63$ mL; $SD = 0.13$, range 0.5 – 0.9 mL) and adolescents ($M = 0.88$ mL; $SD = 0.23$, range 0.6 – 1.3 mL) ($p = 0.16$); however, children had significantly smaller mean equivalent ECV compared to adults ($M = 1.0$ mL; $SD = 0.25$, range 0.7–1.5 mL), ($p < 0.0001$). Differences in ECV between adults and adolescents were not significant ($p = 0.19$).

The resulting regression model for cVEMP threshold using a 500 Hz TB was: $y = 16.35 * X + 96.64$, where $Y =$ threshold response and $X =$ ECV], indicating that at 500 Hz, cVEMP threshold decreases by 1.635 dB for each 0.1 mL decrease in equivalent ECV. For 750 Hz, the regression model for cVEMP threshold was: $y = 16.24 * X + 96.41$, where cVEMP threshold decreases by 1.624 dB for each 0.1 mL decrease in equivalent ECV. For oVEMP, the resulting regression model using a 500 Hz TB was: [$y = 14.65 * X + 102.00$], indicating that oVEMP threshold decreases by 1.465 dB for each 0.1 mL decrease in equivalent ECV. For a 750 Hz TB, the regression model for oVEMP threshold was: $y = 12.50 * X + 104.60$, where oVEMP threshold decreases by 1.250 dB for each 0.1 mL decrease in equivalent ECV.

Collectively, VEMP results suggest that in children, adolescents, and young adults, there were no differences in c- and oVEMP response rates, respective latencies, peak-to-peak amplitudes, and thresholds when comparing 500 Hz and 750 Hz stimulus frequencies. However, when assessing differences in thresholds across age groups, children had significantly lower c- and oVEMP thresholds and smaller ECV values compared to adults at both 500 Hz and 750 Hz. For both c- and oVEMP, threshold has a linear relationship with equivalent ECV.

Cochlear Changes Following c- and oVEMP Testing using 500 Hz and 750 Hz TB Stimuli

Audiometric Threshold Testing—To determine the effect of VEMP threshold testing on audiometric thresholds, a repeated measures ANOVA was performed to examine the main effects of time (pre-VEMP vs post-VEMP) and audiometric frequency (500, 750, 1000, 1500, 2000, 3000, 4000, and 6000 Hz) on audiometric threshold. For children-adolescents

and adults exposed to either a 500 Hz or 750 Hz VEMP stimulus, there was no main effect of time, audiometric frequency, or interaction between time and frequency on audiometric threshold from pre- to post-VEMP threshold testing (all p -values > 0.05 ; see Table 3). As shown in Figure 2, audiometric thresholds from pre- to post-VEMP testing did not shift more than 5 dB HL in either ear at any of the frequencies tested for children, adolescents, or adults.

DPOAE Amplitude—For each subject, the DPOAE amplitude difference (post- DPOAEs subtracted from the pre- DPOAE average) was compared to the 95% CI. Similar to the methods performed in Rodriguez et al. (2018), the 95% CI was calculated from the two pre-VEMP DPOAE trials to adjust for test-retest variability. From pre- to post-VEMP, all subjects exhibited DPOAE amplitude differences that were within the 95% CI (refer to Table 4). For children-adolescents, and adults exposed to a 500 Hz or 750 Hz VEMP stimulus, there was no main effect of time, audiometric frequency, or interaction between time and frequency on DPOAE amplitude from pre-to-post VEMP threshold testing (all p -values > 0.05 ; see Table 5). Together, these results suggest that there is no significant decrease in audiometric thresholds or DPOAE amplitude at the tested frequencies post-VEMP threshold testing when using a 500 or 750 HZ TB stimulus.

Subjective Questionnaire—None of the subjects [children (0/10); adolescents (0/10); adults (0/10)] reported symptoms consistent with otologic or auditory changes from pre-to-post-VEMP in either ear that was exposed.

DISCUSSION

At this time, data on c- and oVEMP thresholds are minimal and frequency tuning and the impact of sound exposure in children and adolescents have yet to be discussed. The primary goal of the study was to determine VEMP threshold and frequency tuning responses and its impact on cochlear function in children and adolescents. It was hypothesized that children, adolescents, and young adults would demonstrate reliable VEMP responses at levels below maximum stimulation (e.g., 120 – 125 dB SPL) and similar frequency tuning to 500 and 750 Hz (Piker et al. 2013). In addition, by utilizing recommended allowance for safe sound exposure level (< 132 dB SPL; EU 2003) and equivalent ECV (Rodriguez et al. 2018) as metrics to guide stimulation level, cochlear changes would be avoided post c- and oVEMP threshold testing regardless of which stimulus frequency was used.

VEMP Thresholds

VEMP thresholds in the adult population have been widely investigated. Janky and Shepard (2009) determined that within their young adult group (ages 20–29 years), mean cVEMP thresholds were ~113 dB SPL at both 500 Hz and 750 Hz TB. Our young adult data were similar to these findings; Mean cVEMP thresholds were 111.5 dB SPL for 500 Hz and 112 dB SPL at 750 Hz. We also determined that oVEMP thresholds in young adults (500 Hz mean= 116 dB SPL; 750 Hz mean= 117 dB SPL) were greater than cVEMP, however, are within 10 dB of each other, similar to data represented by Park et al. (2010).

In the present study, our primary aim was to determine both c- and oVEMP thresholds for children and adolescents at 500 Hz and 750 Hz. Results revealed that thresholds could be obtained in children and adolescents and as anticipated, mean c- and oVEMP thresholds were well below high stimulation levels (i.e., 120 dB SPL) for both frequencies. In response to a 500 Hz TB, our mean VEMP thresholds were in agreement with previous cVEMP findings in children with normal hearing. Zhou et al. (2009) determined that children (ages 4–18) had mean cVEMP thresholds at ~ 105 dB SPL (74 dBnHL). Similarly, Maes et al. 2014 determined that cVEMP thresholds were ~100 dB SPL (70 dBnHL) for children ages 10–13 years and ~105 dB SPL (73 dBnHL) for children ages 4–9 years. oVEMP thresholds were also in a similar range as noted by Piker et al. (2011) and Xu et al. (2015) who found mean oVEMP thresholds to be ~ 115 dB SPL in children (ages 4–18). To the authors' knowledge, there are no normative threshold values obtained at 750 Hz in children aside from our data.

Additionally, our results did show that children (ages 4–10) had significantly lower c- and oVEMP thresholds compared to young adults (refer to Table 2). It is well documented that there is an effect of age on VEMP thresholds in the adult VEMP literature; VEMP thresholds significantly increase with age in older adulthood when using a click (Welgampola & Colebatch 2001) or TB (Janky & Shepard 2009) stimulus. For example, Piker et al. (2011) showed that oVEMP thresholds increase as a function of age in a subgroup of children (n= 20; ages 8–18 years) through older adults, with the largest increase seen for their older adult population. Anatomical changes to the otolith are believed to explain why older adults have higher thresholds than younger adults; Due to increased stiffness to the otolith structures related to aging, a greater amount of dB SPL is needed to stimulate the organs for a reliable response (Piker et al. 2013; Jacobson & Shepard 2016). However, the greatest age effects seen in increased c- and oVEMP thresholds are often seen in adults 50 years and older (Janky & Shepard 2009; Piker et al. 2011). Given the age range in the present study (children through adolescents = 4–19 years; adults = 20–29 years), it is not suspected that age-related changes to the otolith are mediating the threshold differences seen in the present study. Rather, it is more likely that the smaller equivalent ECVs observed in children (ages 4–10), which results in greater total peSPL delivered to the ear for otolith stimulation, can explain the lower VEMP thresholds seen in this younger age range when compared to young adults.

Physiologic factors, such as ear canal length, middle ear impedance, and volume of the ear canal can alter the total SPL delivered to the ear. It is well evidenced that children with smaller ear canals have higher SPL recordings compared to individuals with larger ear canals, despite identical middle ear admittance (Shanks 1984). In relation to using VEMP stimuli, previous findings have shown that due to a smaller equivalent ECV, children receive ~ 3 dB increase in peSPL compared to adults in response to a 500 Hz TB stimulus and as equivalent ECV decreases for every 0.1 mL, peSPL level increases by 0.58 dB (Thomas et al. 2017; Rodriguez et al. 2018). Collectively, this suggests that the amount of SPL a child receives in the ear canal during VEMP testing is not equivalent to what an adult receives despite the use of a similar stimulation level and advocates that ECV should be taken into consideration when performing VEMP testing in children. Based on our findings, it is plausible that children with smaller ECV as seen the current study (Children: M= 0.63, SD=

0.13) could have lower thresholds because they received higher SPLs to stimulate the otolith compared to the adults ($M= 1.0$, $SD= 0.25$), who represented the larger ECV values. While effects of age group were noted in the present study, the findings are believed to be attributed to increases in ECV, with increasing age. Previous research has emphasized a relationship between ECV and age; infants show the greatest differences compared to adults (Keefe et al. 1993), although significantly smaller ECVs continue through early childhood (Nozza et al. 1992; De Chicchis et al. 2000).

In the current study, cVEMP p13 and n23 latencies were significantly shorter for children compared to young adults. These findings are consistent with previous reports (Kelsch et al. 2006; Maes et al. 2014; Rodriguez et al. 2018) where shorter p13/n23 latencies are attributed to vestibulo-colic reflex pathways that may not be fully developed in younger children or anatomical variants (e.g., neck length, head size) that are physically smaller in young children (Sheykhosami et al. 2005; Chang et al. 2007; Zagólski 2007). Children, adolescents, and young adults also show no significant difference for oVEMP peak-to-peak amplitudes or respective latencies (Hsu et al. 2009; Piker et al. 2011). It is suggested that oVEMPs emerge after the age of 2 years in conjunction the vestibular-ocular-reflex response (Hsu et al. 2009). The lack of age related changes suggest oVEMP responses are immediately adult-like (Welgampola & Colebatch 2001; Su et al. 2004; Chang et al. 2007). While it has been documented that younger children (1 to 3 years) have smaller oVEMP peak-to-peak amplitudes compared to children > 4 years, there is no significant correlation between age and amplitude in this age range (Wang et al. 2013). As such, we speculate the smaller amplitudes seen in younger children could be attributed to difficulty sustaining maximum up-gaze for the duration of testing.

Frequency Tuning between 500 Hz and 750 Hz TB

The second aim of the present study was to determine if frequency tuning differences existed between 500 Hz and 750 Hz TB in children, adolescents, and adults. Results showed no difference in c- and oVEMP response rates, peak-to-peak amplitudes, or thresholds for all groups between either stimulus frequency, suggesting that children, adolescents, and young adults show similar frequency tuning at 500 Hz and 750 Hz. While this is the first frequency tuning data to be represented in the pediatric population, results are consistent with earlier findings related to frequency tuning of the vestibular system in the younger-and middle-aged adult population. Welgampola and Colebatch (2001) were the first to determine that the largest cVEMP amplitude occurred at ~700 Hz. Akin et al. (2003) reported the largest cVEMP amplitudes with the lowest thresholds at 500 to 750 Hz with no effect on p13/n23 latencies. More recent evidence has also shown that young adults (ages 18 – 39) show similar responses rates (100%) when using a 500 Hz and 750 Hz TB stimulus for cVEMP (Janky & Shepard 2009). Piker and colleagues (2013) have further described that younger-and middle-aged adults tend to show a peak response at 750 Hz, as evidenced by higher peak-to-peak c- and oVEMP amplitudes and increased response rates when compared to 500 Hz.

Impact on Sound Exposure

The third purpose of the present study was to determine the impact of VEMP threshold testing using a 500 Hz or 750 Hz TB stimulus on cochlear function which has yet to be investigated in the adult and pediatric population. It was hypothesized that by utilizing the VEMP stimulus parameters in the methodology (i.e., shorter duration and lower stimulation level respective to equivalent ECV) and abiding by safe sound energy exposure guidelines (EU 2003), there would not be significant change in outer hair cell function in children, adolescents, and young adults when exposed to a 500 Hz or 750 Hz TB stimulus. Similar to Rodriguez et al. (2018), stimulus parameters were chosen to best minimize sound energy exposure during all VEMP testing. The parameters included using a shorter duration (i.e., 1 cycle rise/fall; 0 cycle plateau) and reducing maximum stimulation level to 120 dB SPL when equivalent ECV = 0.8 mL. For threshold testing in children and adolescents, an ascending approach was also used to limit the number of high intensity stimuli required to obtain a threshold value.

Total sound energy exposure was calculated using the following formula: intensity (SPL) – 3 dB (A – weighting) + $10 \times \log_{10}$ (stimulus duration in seconds) with a recommended allowance for total sound energy < 132 dB SPL in the tested ear.

However, to be conservative, the A - weighting filter was not subtracted from the peSPL intensity to determine total energy exposure because an A-weighted filter is not consistent with the nature of a VEMP stimulus. Rather, a VEMP stimulus is better described as a single TB frequency with a short duration and in line with a C - weighted scale that is used for particularly characterizing low-frequency sounds (ANSI 2013; refer to Discussion in Rodriguez et al. 2018). Additionally, when using this equation with children, we added 3 dB when calculating sound energy exposure to account for peSPL differences related to ECV (Rodriguez et al. 2018).

Using the formula as described, we calculated the total sound energy exposure for c-and oVEMP threshold testing using a 500 Hz and 750 Hz TB. On average, children received 6 trials for each c-and oVEMP (1,500 total stimuli; no subtraction of 3 dB for A-weighting, +3 dB for a child). The total sound energy exposure that a child in our study received was below the recommended total sound energy limit of 132 dB HL (Colebatch & Rosengren 2014) using a 500 Hz TB (127 dB SPL) and 750 Hz TB (125.2 dB SPL), which produced less total sound exposure, comparatively.

Using these approaches to minimize sound exposure, audiometric threshold and DPOAE amplitude results from our study showed no significant change in outer hair cell function from pre- to post-VEMP using a 500 Hz or 750 Hz TB stimulus. Additionally, our findings did not reveal a change in otologic symptoms across subjects. Collectively, these findings support our hypothesis. While previous studies performed in adults have reported subjective and objective changes in hearing status following VEMP exposure (e.g., aural fullness and tinnitus) (Krause et al. 2013; Mattingly et al. 2015; Stromberg et al. 2016), it is reasoned that those findings were related to a combination of high number of stimuli used (e.g., up to 800 stimuli), high stimulation level (e.g., 135 dB SPL), and longer stimulus durations (e.g., 10 ms) that increased the overall sound energy exposure (Colebatch & Rosengren 2014).

Shortening the stimulus as recommended by Colebatch and Rosengren (2014) reduces unsafe sound exposure, while reliable VEMPs can be obtained as evidenced in adults Rosengren (2009) and children with normal hearing (Rodriguez et al. 2018). It is advocated that for TB-evoked VEMP responses, a stimulation level less than the traditional 125 dB SPL should be utilized as multiple repetitions of each stimulus may be needed, such as in VEMP threshold testing, and energy exposure should be considered (Welgampola & Colebatch 2001). We also suggest that less sound exposure can be avoided at high intensity levels when an ascending threshold search is employed. Based on our findings, we do not suspect that the different methods used to determine threshold (descending vs ascending) had a significant effect on the results, as thresholds were confirmed in the same manner for all groups. Similarly, we do not suspect that the manner in which the subjective questionnaire was administered impacted our findings. Questions were both physically presented as well as read aloud. For younger children, this was particularly important as there was no reliance on their literacy skills. All subjects responded reliably to all questions and results were consistent with the lack of observed significant changes in pre- to post-audiometric thresholds or DPOAE amplitudes across subjects.

Another important aspect that can affect the duration of the stimulus is the rise/fall and plateau time. Shorter rise/fall times will result in lower energy and shorter stimuli duration compared to longer rise/fall times (Rosengren et al. 2009). In the present study, we used a 1 cycle rise/fall and 0 cycle plateau for all VEMP testing. This equates to 2 ms rise/fall (total of 4 ms) for 500 Hz TB and 1.33 ms rise/fall (total of 2.67 ms) for 750 Hz TB. Previously we have shown this to result in 100% response rates in children (Rodriguez et al. 2018). The rationale for using these parameters was two-fold. Primarily, Singh and Apeksha (2014) reported that when the plateau time was held constant at 0 ms, there was no significant difference in cVEMP amplitudes when rise/fall times of 1 ms to 7 ms were used. For oVEMP, Lim et al. (2013) determined that increasing the total stimulus duration produced a reduction in oVEMP amplitude and there was no definitive advantage in increasing the stimulus duration beyond 2 to 4 ms.

Secondly, shorter stimuli duration decreases unnecessary sound energy exposure delivered to the ear (Colebatch & Rosengren, 2014; Singh & Apeksha 2014). Using a shorter duration also allows for more repetitions to be made without exceeding unsafe exposure limits (i.e., > 132 dB). This is particularly advantageous for children because they receive greater peSPL in response to VEMP stimuli and could require more repetitions to verify a response as compared to adults. While Welgampola and Colebatch (2001) and Papathanasiou et al. (2014) suggest using a maximum of 7 ms stimulus duration with 1 cycle plateau, these recommendations are based on data from the adult ear and should be carefully considered prior to translating to the pediatric population for concerns of unsafe-sound exposure.

While bone-conduction VEMP testing may be considered optimal in children, air-conduction testing is widely used in both adult and pediatric protocols. Recent work has shown that children who receive VEMP testing have an increased risk of noise exposure if adult-like stimulus parameters are used (Thomas et al. 2017; Portnuff et al. 2017). Due to the variability in testing children, additional stimuli may be necessary. Factors such as reduced or inconsistent muscle contraction, fatigue, or non-compliance can influence the number of

stimuli needed to obtain a reliable response. In the present study, EMG monitoring for cVEMP testing was performed. If SCM contraction was below the set EMG range (50–300 μV), the stimuli were rejected from the final number of sweeps but was still delivered to the ear, thus increasing total sound exposure for that particular subject. Over the total duration of the VEMP threshold testing, the maximum number of rejected stimuli for one child was 83 and 25 for one adult. When factored in the maximum number of rejected stimuli as seen in this study, the total sound energy exposure that a child or adult in our study could have received was still under the recommended 132 dB allowance for a 500 Hz TB (Child: 131.0 dB SPL; Adult: 131.8 dB SPL) and 750 Hz TB stimulus (Child: 129.2 dB SPL; Adult: 130.0 dB SPL). Evidence from the present study justifies recommendations of lowering the maximum stimulation level based on equivalent ECV and utilizing an ascending approach when obtaining VEMP thresholds to minimize the risk of unsafe sound exposure during VEMP testing in children.

While it is well-documented that c- and oVEMP responses can be reliably measured in children using a 500 Hz TB stimulus (Su et al. 2004; Hsu et al. 2009; Janky & Givens 2015), the present study is the first to document reliable VEMP responses in children and adolescents using a 750 Hz TB stimulus. Frequency tuning results from the current study suggest that a 750 Hz TB stimulus frequency has the same diagnostic capability as a 500 Hz TB for children, adolescents, and young adults. However, previous probe microphone measurements have shown a reduction of SPL delivered to the ear when using a higher frequency due to its shorter duration; Children receive less peSPL (~ 2 dB) in the ear in response to a 750 Hz VEMP stimulus compared to a 500 Hz (Rodriguez et al. 2018). Therefore, while neither stimulus (500 Hz or 750 Hz) results in cochlear changes following VEMP testing, using a 750 Hz TB could be regarded as the safer stimuli, due to its shorter duration and thus reduced sound exposure. While not evaluated in the present study, we speculate these VEMP settings would be clinically reliable for children with sensorineural hearing loss as VEMP responses are not affected by the presence of hearing loss alone (Colebatch & Halmagyi 1992).

Another method to reduce sound exposure secondary to VEMP is to employ the use of a bone-conduction stimulus. While less is known about the effects of safety in performing bone conduction VEMP testing (Papathanasiou et al. 2014), the use of bone vibration (e.g., minishaker, reflex hammer tap) has been performed in adults (Halmagyi et al. 1995; Nguyen et al. 2010; Rosengren et al. 2011; Wackym 2012;) and children (Monobe & Murofushi 2004; Zhou et al. 2014) with advantages. For one, bone conduction VEMP responses have been shown to be more reliable and robust than air-conduction responses (Brantberg et al. 2003; Cheng et al. 2009; Wackym et al. 2012). Secondly, bone conduction VEMP responses can be generated in the presence of conductive hearing loss (Halmagyi et al. 1995) and used in children with middle ear issues (Monobe & Murofushi 2004; Zhou et al. 2014). Using bone conduction also bypasses the need to account for ECV. However, at this time research on pediatric VEMP testing using bone conduction are limited. Further investigations regarding optimized clinical protocols that encompass safety and reliability of bone conducted responses in children are still needed.

CONCLUSION

Findings from this study revealed that reliable VEMP thresholds can be obtained in children, adolescents, and young adults at lower intensities (i.e., 120 dB SPL) than the standard high intensities (i.e., 125 dB SPL), similar frequency tuning responses are present when using a 500 Hz or 750 Hz TB stimulus, and there is no change in outer hair cell function when using either stimulus frequency. These results provide justification that VEMP thresholds can be safely determined in children, adolescents, and young adults. As such, clinicians can use these data to guide how they perform air-conducted VEMP testing in children. Presenting at a lower stimulation level (i.e., < 120 dB SPL) and using a 750 Hz stimulus can be used with appropriate diagnostic capability, while lessening the risk of acoustic trauma secondary to the VEMP testing procedure. When using air-conducted VEMP, it is then recommended to interpret thresholds based on the child's ECV and age. Future work implementing similar VEMP settings in children with vestibular loss is warranted.

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

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A. I. R designed and performed experiments, analyzed the data, and wrote the article; M. L. A. T. and K. L. J. designed and performed experiments and provided critical revision of the manuscript.

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Figure 1. Relationship Between Cervical (top) and Ocular (bottom) VEMP Threshold to Age (left) and Equivalent ECV (right) for 500 and 750 Hz TB

Line in each graph represents regression line through the data. Significant relationship between age and ECV and VEMP threshold; ECV is a stronger predictor.

Figure 2. Mean Audiometric Threshold Difference (pre-to-post VEMP Threshold testing) for Children- Adolescents and Adults with Normal Hearing for 500 Hz (left) and 750 Hz (right) VEMP Stimulus Frequencies

Solid line represents child-adolescent threshold mean difference and hashed line represents adult threshold mean difference. No significant difference in audiometric thresholds from pre-to-post VEMP threshold testing for all subjects.

Figure 3.
Electrode montage for cVEMP (A) and oVEMP (B).

Table 1
Mean (SD) VEMP Characteristics at Maximum Stimulation Level for 500 Hz and 750 Hz TB

Cervical VEMP		750 Hz					
500 Hz		p13	n23	AMP	EMG	CA	
Adults		13.92 (1.08)	22.20 (1.77)	223.17 (99.18)	175.50 (44.60)	1.27 (0.50)	13.57 (1.52)
Adolescents		13.77 (1.19)	20.93 (2.13)	371.00 (206.1)	173.0 (39.63)	0.78 (0.32)	13.19 (1.63)
Children		12.25 (1.46)	19.25 (2.36)	360.60 (185.7)	152.41 (40.18)	0.68 (0.25)	12.32 (1.92)
Ocular VEMP		750 Hz					
500 Hz		n10	p16	AMP			
Adults		10.10 (1.03)	14.56 (1.18)	16.59 (7.55)			
Adolescents		10.08 (1.67)	15.66 (1.61)	14.55 (9.60)			
Children		10.59 (1.64)	15.31 (2.40)	12.06 (8.36)			

Bolded values indicate significance (ANOVA with post-hoc analysis: Adults had longer p13 and n23 latencies compared to children, adolescents had longer p13 and n23 latencies than children). AMP, uncorrected peak-to-peak amplitude; EMG, electromyography; CA, corrected peak-to-peak amplitude; TB, toneburst; VEMP, vestibular evoked myogenic potential. p13/n23 and n10/p16 latencies recorded in milliseconds (ms); AMP, EMG, and CA recorded in microvolts (μ V).

Table 2

Mean (SD) VEMP Thresholds for 500 Hz and 750 Hz TB

	500 Hz	750 Hz
Cervical VEMP Threshold Response (dB SPL)		
Adults	111.5 (3.25)	112 (2.61)
Adolescents	107.5 (4.85)	109.5 (3.68)
Children	106 (4.63)	106 (3.91)
Ocular VEMP Threshold Response (dB SPL)		
Adults	116 (3.94)	117 (3.49)
Adolescents	112.5 (4.81)	114.5 (2.83)
Children	111.1 (4.10)	112.2 (4.17)

Bold values represent significance (ANOVA with post-hoc analysis: Children had lower c- and oVEMP thresholds compared to adults); VEMP, vestibular evoked myogenic potential; c- and oVEMP thresholds recorded in decibel sound pressure level (dB SPL).

Table 3

Statistical Results for Audiometric Thresholds per VEMP Stimulus Frequency

Main Effect	VEMP Stimulus- 500 Hz TB		VEMP Stimulus- 750 Hz TB	
	Child- Adolescent	Adult	Child- Adolescent	Adult
Time (pre-to-post VEMP)	F(1, 19) = 0.95 <i>p</i> = 0.60	F(1, 9) = 2.95 <i>p</i> = 0.12	F(1, 19) = .53 <i>p</i> = 0.76	F(1, 9) = 4.74 <i>p</i> = 0.10
Audiometric Frequency	F(7, 13) = 0.17 <i>p</i> = 0.68	F(7, 3) = 0.72 <i>p</i> = 0.68	F(7, 13) = 2.47 <i>p</i> = 0.19	F(7, 3) = 1.37 <i>p</i> = 0.43
Interaction (time vs frequency)	F(7, 13) = 0.60 <i>p</i> = 0.67	F(7, 3) = 1.32 <i>p</i> = 0.45	F(7, 13) = 0.90 <i>p</i> = 0.53	F(7, 3) = 0.79 <i>p</i> = 0.64

TB, toneburst; VEMP, vestibular evoked myogenic potential

Table 4

Pre-VEMP DPOAE Test-Retest 95% Confidence Intervals for Children- Adolescents and Adults and DPOAE Amplitude Mean Difference Between Pre and Post- VEMP Threshold Testing

Fq (kHz)	Child- Adolescent					Adult				
	500 Hz		750 Hz			500 Hz		750 Hz		
	VEMP Fq	Pre-Post DPOAE Amp Diff	VEMP Fq	Pre-Post DPOAE Amp Diff	95% CI	VEMP Fq	Pre-Post DPOAE Amp Diff	VEMP Fq	Pre-Post DPOAE Amp Diff	95% CI
	95% CI		95% CI			95% CI		95% CI		
0.75	-3.8 to 3.1	0.2	-4.1 to 3.8	0.1		-1.9 to 1.8	0.5	-1.6 to 1.1	-0.9	
1	-2.4 to 4.1	-0.3	-2.1 to 3.3	0.5		-1.0 to 2.9	0.9	-1.4 to 1.0	-0.3	
1.5	-3.8 to 4.0	1.1	-3.1 to 3.1	0.5		-1.6 to 1.9	0.2	-2.4 to 1.4	-0.5	
2	-2.9 to 3.1	-0.1	-3.8 to 4.0	0.2		-1.2 to 2.0	-0.4	-2.5 to 2.8	0.1	
3	-3.3 to 2.8	-1.2	-2.6 to 2.7	-0.4		-1.4 to 1.5	0.5	-2.1 to 2.1	0.2	
4	-2.3 to 2.3	0.5	-1.0 to 3.7	-0.5		-1.8 to 2.9	0.3	-2.0 to 2.3	0.1	
6	-2.8 to 2.7	1.4	-1.9 to 3.7	0.5		-1.8 to 2.7	-0.6	-2.7 to 4.5	1.9	
8	-2.0 to 1.8	-0.5	-1.0 to 2.5	-0.8		-1.7 to 1.5	-0.1	-2.8 to 2.5	0.8	

CI, confidence interval; Fq, frequency; DPOAE, Distortion Product Otoacoustic Emissions; Amp, amplitude; VEMP, vestibular evoked myogenic potential; 95% CI and DPOAE Amp Diff recorded in decibel (dB).

Table 5

Statistical Results of DPOAE Amplitude per VEMP Stimulus Frequency

Main Effect	VEMP Stimulus- 500 Hz TB		VEMP Stimulus- 750 Hz TB	
	Child- Adolescent	Adult	Child- Adolescent	Adult
Time (pre-to-post VEMP)	$F(1, 19) = 3.53$ $p = 0.08$	$F(1, 9) = 5.4$ $p = 0.30$	$F(1, 19) = 2.71$ $p = 0.13$	$F(1, 9) = 0.95$ $p = 0.36$
Audiometric Frequency	$F(7, 13) = 2.64$ $p = 0.10$	$F(7, 3) = 0.77$ $p = 0.65$	$F(7, 13) = 1.70$ $p = 0.20$	$F(7, 3) = 1.06$ $p = 0.39$
Interaction (time vs frequency)	$F(7, 13) = 0.22$ $p = 0.97$	$F(7, 3) = 1.19$ $p = 0.49$	$F(7, 13) = 2.5$ $p = 0.24$	$F(7, 3) = 3.30$ $p = 0.18$

DPOAE, Distortion Product Otoacoustic Emissions; TB, toneburst; VEMP, vestibular evoked myogenic potential