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Effects of High Sound Exposure During Air-conducted Vestibular Evoked Myogenic Potential Testing in Children and Young Adults

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Abstract

Objectives—Vestibular evoked myogenic potential (VEMP) testing is increasingly utilized in pediatric vestibular evaluations due to its diagnostic capability to identify otolith dysfunction and feasibility of testing. However, there is evidence demonstrating that the high intensity stimulation level required to elicit a reliable VEMP response causes acoustic trauma in adults. Despite utility of VEMP testing in children, similar findings are unknown. It is hypothesized that increased sound exposure may exist in children as differences in ear canal volume compared to adults and the effect of stimulus parameters (e.g., signal duration and intensity) will alter exposure levels delivered to a child's ear. The objectives of this study are to (1) measure peak-to-peak equivalent sound pressure levels (peSPL) in children and young adults with normal hearing (CNH; ANH) using high intensity VEMP stimuli, (2) determine the effect of ear canal volume on peSPL and calculate a safe exposure level for VEMP and, (3) assess whether cochlear changes exist following VEMP exposure.

Design—This was a two-phase approach. Phase I: 15 CNH and 12 ANH participated. Equivalent ear canal volume was measured. In one ear, peSPL was recorded for 5 seconds at 105–125 dB SPL, in 5 dB increments for 500 and 750 Hz tone bursts. Recorded peSPL values (accounting for stimulus duration) were then used to calculate safe sound energy exposure values for VEMP testing using the 132 dB recommended energy allowance from the 2003 European Union Guidelines. Phase II: 15 CNH and 10 ANH received cervical and ocular VEMP testing in one ear. Subjects completed tympanometry, pre- and post- audiometric threshold testing, DPOAEs, and questionnaire addressing subjective otologic symptoms to study the effect of VEMP exposure on cochlear function.

Results—(1) In response to high intensity stimulation levels (e.g., 125 dB SPL), CNH had significantly higher peSPL measurements and smaller ear canal volumes compared to ANH. (2) A significant linear relationship between equivalent ear canal volume (as measured by diagnostic tympanometry) and peSPL exists and has an effect on total sound energy exposure level; based on data from Phase I, 120 dB SPL was determined to be an acoustically safe stimulation level for

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testing in children. (3) Using calculated safe stimulation level for VEMP testing, there were no significant effect of VEMP exposure on cochlear function (as measured by audiometric thresholds, DPOAE amplitude levels, or subjective symptoms) in CNH and ANH.

Conclusions—peSPL sound recordings in children's ears are significantly higher (~ 3 dB) than adults in response to high intensity VEMP stimuli that are commonly practiced. Equivalent ear canal volume contributes to peSPL delivered to the ear during VEMP testing and should be considered to determine safe acoustic VEMP stimulus parameters; children with smaller ECVs are at risk for unsafe sound exposure during routine VEMP testing and stimuli should not exceed 120 dB SPL. Using 120 dB SPL stimulus level for children during VEMP testing yields no change to cochlear function and reliable VEMP responses.

INTRODUCTION

Despite the common use of air-conducted cervical and ocular vestibular evoked myogenic potentials (c-and oVEMP, respectively), the VEMP response is elicited with a high intensity presentation acoustic signal (i.e., 125 dB SPL) that may cause harmful sound exposure in children. The cVEMP is an inhibitory response obtained from the sternocleidomastoid (SCM) muscle (Colebatch et al. 1994). It is considered to be a reflection of vestibulospinal projections to the ipsilateral SCM, and provides information regarding saccule and inferior vestibular nerve integrity (Colebatch & Halmagyi 1992; Robertson & Ireland 1995). The oVEMP is an excitatory response obtained from the inferior oblique (extra-ocular) muscle. The pathway of the oVEMP response extends from the utricle to superior vestibular nerve and crosses to the contralateral inferior oblique muscle. While it is speculated that oVEMPs predominately assess utricular and inferior nerve function; it may also reflect contributions from the saccule (Todd et al. 2007; Curthoys et al. 2010; Weber et al. 2012).

Due to the anatomical similarities between the vascular supply, membranous labyrinth, and receptor cells of the cochlea and vestibule, inner ear disease that affects both the hearing and balance organs is not uncommon in the pediatric population (Inoue et al. 2013). Thirty to 70 percent of children with profound sensorineural hearing loss (SNHL) have some degree of vestibular dysfunction (Buchman et al. 2004; Jafari & Malayeri 2011). Impaired saccular and utricular function has been specifically observed in 40 percent of children with severe to profound SNHL (Xin-Da Xu et al. 2015). When vestibular testing is necessary for children, VEMP testing is considered diagnostically important for the pediatric vestibular evaluation given it can provide assessment of otolith organ function, provide ear-specific information, and it is feasible to administer (O'Reilly et al. 2013). While VEMPs are commonly performed in adults and now being applied in pediatric evaluations, less is known about potential consequences (e.g., acoustic trauma) that could affect children during testing.

Temporary changes in outer hair cell function in adults have been documented following VEMP exposure (Young 2006). After cVEMP testing, an immediate reduction in distortion product otoacoustic emissions (DPOAEs) and aural fullness has been reported (Krause et al. 2013; Stromberg et al. 2015). Additionally, in a single-case report, a sudden sensorineural hearing loss was observed post-VEMP exposure as evidenced by decreased speech recognition scores and increased pure-tone audiometric thresholds (Mattingly et al. 2015).

While some argue that VEMPs in the clinical setting are thought to be safe, as the amount of sound energy is not enough to permanently affect cochlear function (Welgampola & Colebatch 2005), there is concern that the high pressure acoustic stimuli (e.g., 125 dB SPL) required to elicit reliable and repeatable VEMP responses may result in cochlear damage in highly susceptible ears (e.g., young children). Ear canal volume (ECV) are considered to be smaller in children compared to adults and typically increase in size with maturation (Margolis & Heller 1987; Chicchis et al. 2000), however other anatomical differences such as average ear canal length and increased compliancy of the external auditory canal (Margolis & Shanks 1985) can also increase the sound pressure level (SPL) that is delivered to the cochlea. Feigin, Kaplin, Stelmachowicz, and Gorga (1989) measured SPL generated in the ear canal in children from 1 month to 5 years of age and determined that children averaged 4 dB higher SPL compared to adults that decreased with age, but still present at 5 years of age. More recent studies investigating the range of peak-to-peak equivalent sound pressure levels (peSPLs) in child and adult ears in response to high intensity tone burst and click stimuli (i.e., 100 dB normalized hearing level) have been performed to determine if acoustic stimulus levels with VEMP testing were safe for use in children. Measurements taken in response to low intensity stimuli suggested peSPL recordings are approximately 3 dB higher in a child's ear compared to an adult ear and higher stimulus presentations may be in excess of noise regulations in a child's ear (Thomas et al. 2016).

There are limited recommendations available to guide clinicians and researchers regarding safe sound exposure for diagnostic testing similar to that of VEMP testing (Portnuff et al. 2017). Previous research investigating sound exposure following VEMP testing (Young 2006; Krause et al. 2013; Stromberg et al. 2015) or procedures such as suctioning of middle ear effusion (Wang et al. 2014) have abided by standards used from the Occupational Safety and Health Administration (OSHA) and The National Institute for Occupational Safety and Health (NIOSH). These organizations recommend that the total sound energy exposure measured during a specific period (e.g., 8-hour work day), whether that be continuous, impulse, or intermittent noise, should not be greater than 140 dBC SPL. Although, these traditional guidelines are not intended to be utilized in medical contexts and do not consider stimulus parameters that characterize VEMP testing. Stimulus duration and intensity of the signal will affect the total sound energy delivered to the ear during VEMP testing; longer stimuli contain proportionately greater sound energy (Colebatch & Rosengren 2014; Portnuff et al. 2017). Colebatch and Rosengren (2014) recommended that calculating sound energy exposure (ANSI 2013), which accounts for both intensity and duration of the stimulus, is a preferred method to evaluate sound exposure related to VEMP testing. Sound energy exposure can be calculated as: $\text{Stimulus Level (in SPL)} - 3\text{dB (A-weighted filter)} + 10 \times \log_{10}(\text{stimulus duration in seconds})$, with an allowance of 132 dB SPL considered as the maximum cutoff in accordance with guidelines from the European Union (2003).

Evidence demonstrates adverse effects on cochlear function in adults following o- and cVEMP testing. However, it is unknown if similar adverse effects occur in children. Cochlear damage to children during routine vestibular testing would have severe implications and considerations regarding recommended stimulus protocols. Therefore, the purpose of the present study was to: 1) measure peSPLs in children and young adults using short duration VEMP stimuli 2) use recommended sound exposure calculation accounting

for duration and intensity and with 132 dB SPL sound energy maximum allowance (Colebatch & Rosengren, 2014) to determine a safe stimulation level for VEMP testing in adults and children, and 3) assess whether cochlear changes exist following c-and-oVEMP testing, as measured by changes to audiometric thresholds and DPOAE amplitude level. It is hypothesized that based on smaller ECV in ears of children and data documenting 3 dB higher peSPL values in children's ear canals, peSPL measurements will continue to be higher in our child study population at high intensity stimulus levels (e.g., 125 dB SPL). However, utilizing the recommended allowance for safe sound exposure level (< 132 dB SPL), will prevent cochlear changes from occurring post c-and oVEMP testing.

METHODS AND MATERIALS

Phase I

Study Population—Fifteen children with normal hearing (CNH; mean age, 7 years; range, 4–11 years; 5 males) and 12 young adults with normal hearing (ANH; mean age, 32 years; range, 25–42 years; 5 males) participated in the initial phase of this study. By case history, all subjects denied hearing loss, balance/dizziness symptoms, and/or neurological disease. Diagnostic tympanometry using a 226 Hz probe tone (GSI Tympanstar, Grason-Stradler, Eden Prairie, MN, USA) was performed in both ears to record the equivalent ECV and ensure there was appropriate compliance of the tympanic membrane. Tympanometry was considered normal if peak pressure was between –100 and 30 daPa and peak admittance was 0.3 mmhos. Participants who did not meet the above criteria were excluded from the study. Informed consent was obtained from all subjects for testing approved by the Institutional Review Board at Boys Town National Research Hospital.

Sound Pressure Level Measurements—For each subject, one ear was selected at random to serve as the test ear. peSPL measurements were then recorded for ~ 5 seconds at 105–125 dB SPL, in 5 dB increments for 500 and 750 Hz tone burst stimuli. The stimuli were presented using a ICS Chartr 200 Evoked Potential System (GN Otometrics, Taastrup, DK) and delivered to the subject through the VEMP 3A insert earphone transducers. Stimuli consisted of rarefaction onset, at a repetition of rate of 5.1 per second (1 cycle rise/fall time, 0 cycle plateau), with a total duration of 4 msec for 500 Hz and 2.7 msec for 750 Hz. The peSPLs were recorded using a calibrated ER-7C, Series B clinical probe microphone (Etymotic Research, Elk Grove Village, IL, USA) with the gain setting at –20 dB, which enables recording of undistorted output to 140 dB SPL. The probe microphone was attached to an ER7-14C probe tube, which was threaded through the foam portion of the insert earphone (E-A-RLINK 3A [adult] and 3B [child]; 3M Auditory Systems, Indianapolis, IN), which was coupled to the VEMP transducers for each recording (refer to Figure 1 in Thomas et al. 2016) Placement of the insert earphone in the subject's ear was considered optimal if the outer edge of the insert was flush with the external ear canal opening. Waveforms and peak-to-peak voltages were monitored using a Tektronix (Beaverton, OH) TDS 2002 digital oscilloscope. Waveforms were also digitized with a sampling rate of 44.1 kHz then saved using Audacity (version 2.0.4) software. The saved waveform files were imported into Matlab (Mathworks, Natick, MA; Version 2016a) to calculate the peSPL values. To derive the peSPL, the peak-to-peak voltage was measured and converted to pressure using the

microphone sensitivity provided by the manufacturer. The pressure value was then converted to the RMS value used in calculating peSPL as described in Burkard (2006). The waveforms were visually inspected for evidence of distortion; however, no distortion was observed.

Phase II

Study Population—Fifteen CNH (mean age, 7.8 years; range, 12–4 years; 5 males;) and 10 young ANH (mean age, 29.9 years; range, 21–37 years; 4 males) participated in the second phase of this study. Eight children and 3 adults from Phase I, participated in Phase II. By case history, all subjects denied hearing loss, balance/dizziness symptoms, and/or neurological disease. All subjects completed otoscopic inspection and tympanometry in both ears to verify normal middle ear function using the criteria noted above.

Audiometric Threshold Testing—Audiometric thresholds were obtained before (pre-VEMP) and immediately after (post-VEMP) c- and oVEMP testing. Frequencies of 500, 750, 1500, 2000, 3000, 4000, and 6000 Hz were tested in each ear via air conduction using a GSI 61 two-channel diagnostic audiometer (Grason-Stadler, Madison, WI, USA).

Otoacoustic Emissions—DPOAEs were measured using a Bio-logic AuDX Pro Diagnostic Otoacoustic Emissions System (Natus Incorporated, San Carlos, CA) coupled with Scout Otoacoustic Emissions software (Version 3.45.00) 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.

DPOAEs were measured before (pre-VEMP) and less than 10 minutes after (post-VEMP) c- and oVEMP testing with the subject sitting in an upright position. Because DPOAEs are highly influenced by probe-depth variability (Kemp et al., 1998), 2 DPOAE measurements were performed in the subject's left and right ear pre-VEMP to estimate the test-retest variability when comparing pre-and-post DPOAE amplitude. The 95% confidence intervals (CI) of the difference in DPOAE levels between the 2 pre-VEMP trials were calculated for each frequency in all subjects. Post-VEMP, DPOAEs were performed once in both ears. DPOAEs with a signal-to-noise ratio (SNR) less than 6 dB were excluded from the final data analysis. A significant change in SNR DPOAE amplitude related to VEMP testing was analyzed by subtracting the post-VEMP DPOAE amplitude from the averaged pre-VEMP DPOAE amplitude so that a negative value indicated a reduction in the DPOAE amplitude levels. Then, if a difference between pre- and post-VEMP DPOAE was outside of the 95% CI of the 2 pre-VEMP trials, the DPOAE shift was considered significant and less likely influenced by probe depth variability.

Cervical and Ocular VEMP Measurements—For each subject, a test ear was selected at random, with the opposite ear serving as the control, non-test ear. VEMP recordings were completed in the test ear using an ICS Chartr 200 Evoked Potential System (GN Otometrics, Taastrup, DK). Air conduction stimuli were delivered monaurally via ER-3A insert earphones. Stimuli used were 4 msec rarefaction, 500 Hz tone bursts at a repetition of rate of 5.1 per second (Blackman gating window, 1 cycle rise/fall time, 0 cycle plateau). Stimuli

were presented at 125 dB SPL in adults and 120 dB SPL in children. Published VEMP stimulus parameters and guidelines often anywhere from 125–133 dB SPL as the intensity in which VEMP stimuli are delivered (Janky & Shepard 2009; Krause et al. 2013; Piker et al. 2015). Few reports have investigated the potential for noise induced hearing loss secondary to the high intensity stimulation level on changes in cochlear status; these investigations are limited to adult populations which is difficult to generalize to the pediatric population.

For cVEMP testing, an active electrode was placed on the muscle belly of the sternocleidomastoid (SCM) muscle, an electromyography (EMG) electrode just below the SCM electrode, a reference electrode on the manubrium of the sternum, and a ground electrode on the chin. For oVEMP testing, an active electrode was placed under the contralateral eye medio-laterally with a reference electrode on the chin and ground electrode on the manubrium of the sternum. One hundred sweeps were averaged for each cVEMP test, and 150 sweeps were averaged for each oVEMP test. Two trials were completed for each cVEMP and oVEMP recording. For c- and oVEMP, a band-pass filter of 10–1000 Hz and 2–500 Hz was used, respectively.

All subjects lay in a semi-recumbent position for both c- and oVEMP testing. For cVEMP, subjects were instructed to turn their head away from the ear being stimulated and lift their head in response to acoustic stimulation to contract the SCM muscle. EMG was recorded from the ipsilateral SCM between the range of 100–300 (μ V). Measurements included p13 and n23 latencies (msec) and the p13 to n23 peak-to-peak amplitude (μ V). For oVEMP, subjects were instructed to direct their gaze to a mark on the ceiling set at 30 degrees up gaze in response to acoustic stimulation. Measurements included n10 and p16 latencies (msec) and the n10 to p16 peak-to-peak amplitude (μ V). For c- and oVEMP, the presence of a response was considered normal, while an absent response was considered abnormal.

Otologic Subjective Symptom Questionnaire—Pre- and post-VEMP testing, subjects were asked about subjective symptoms pertaining to their hearing (e.g., aural fullness, otalgia, tinnitus, or decreased hearing sensitivity) via a questionnaire.

Statistical Analyses—Repeated measures analysis of variance (ANOVA) was performed to determine if significant changes in hearing thresholds and DPOAE amplitude levels occurred between pre- and post-VEMP testing. A Welch's *t*-test was performed to determine differences in c- and oVEMP latencies and amplitudes between CNH and ANH.

RESULTS

Phase I

Differences in Peak-to-Peak Equivalent Sound Pressure Levels (peSPL) Between Children and Adults with Normal Hearing—Shown in Table 1, peSPL values in CNH were 2.2–2.9 dB higher at each intensity level for 500 and 750 Hz TBs, compared to ANH. In response to a 500 Hz TB at 125 dB SPL, CNH had significantly higher peSPL values ($M=130.0$; $SD=1.7$, range= 126.4–131.8) compared to ANH ($M=127.4.0$; $SD=1.3$, range=125.2–129.3), $p < 0.0001$. In response to a 750 Hz TB at 125 dB SPL, CNH also showed significantly higher peSPL values ($M=127.9$; $SD=1.3$;

range=125.5–130.0) compared to ANH (M=125.7; SD= 1.1; range=123.4–127.4), $p < 0.0001$.

Relationship between Equivalent Ear Canal Volume (ECV) and Peak-to-Peak Equivalent Sound Pressure Levels (peSPL)—CNH had significantly smaller mean ECV (M= 0.7 mL; SD= 0.18, range 0.4 – 0.9) compared to ANH (M=1.1 mL; SD= 0.23, range 0.8–1.5), $p < 0.0001$. There was a linear relationship between ECV and peSPL for 500 and 750 TBs, shown in Figure 1. As ECV size decreased, peSPL increased for both 500 Hz TB [$R^2 = 0.68$, $F(1,25) = 52.28$, $p < 0.0001$] and 750 Hz TB [$R^2 = 0.79$, $F(1,25) = 93.23$, $p < 0.0001$]. For 500 Hz TB in particular, the resulting regression model was: [$y = -5.8 * X + 134.1$, where Y= peSPL and X= ECV], indicating that peSPL decreases by 0.58 dB for each 0.1 mL increase in ECV (as measured by diagnostic tympanometry). Utilizing the regression model equation, total sound energy exposure was then computed for c- and oVEMP testing in one ear to determine the effect of ECV, shown in Table 2. Based on the recommended sound exposure cutoff of 132 dB, children with an ECV less than 0.8 mL would be considered at risk for unsafe sound exposure (> 132 dB, European Unions 2003; Colebatch & Rosengren 2014; *Supplementary Material*, Portnuff et al. 2017).

Phase 2

Quantifying Cochlear Changes Following c- and oVEMP Testing

Audiometric Threshold Testing: A repeated measures ANOVA was conducted to compare the effect of VEMP testing on audiometric thresholds pre- and post-VEMP exposure (Figure 2). In CNH, there was no main effect of time (pre-to-post VEMP testing) [$F(1, 14) = 0.5$; $p = 0.82$] or frequency [$F(7, 8) = 0.85$; $p = 0.39$] on audiometric thresholds in the test-ear. As anticipated, there was no main effect of time [$F(1, 14) = 0.62$; $p = 0.91$] or frequency [$F(7, 8) = 0.77$; $p = 0.41$] was observed in the non-test ear. No interaction was noted for the test-ear [$F(7, 8) = 0.93$; $p = 0.53$] or non-test ear [$F(7, 8) = 0.98$; $p = 0.76$] in CNH. In ANH, there was no main effect of time [$F(1, 9) = 0.32$; $p = 0.58$] or frequency [$F(7, 3) = 0.42$; $p = 0.85$] on audiometric thresholds in the test ear. Similarly, there was no main effect of time [$F(1, 9) = 0.58$; $p = 0.79$] or frequency [$F(7, 3) = 0.67$; $p = 0.89$] was determined in the non-test ear. No significant interaction was observed for the test ear [$F(7, 3) = 0.75$; $p = 0.66$] or non-test ear [$F(7, 3) = 0.87$; $p = 0.71$] in ANH. Audiometric thresholds from pre- to post-VEMP testing did not shift more than 5 dB HL in either ear at all frequencies tested for CNH and ANH. Collectively, these results suggest no significant decrease in audiometric thresholds at the tested frequencies post-VEMP exposure.

DPOAE Amplitude Levels: Each subject's DPOAE amplitude difference (post-DPOAEs subtracted from his/her pre-DPOAEs) was compared to the 95% CI. The 95% CI was calculated from the two pre-VEMP DPOAE tests to account for test-retest variability (Table 3). None of the adult or child subjects demonstrated a DPOAE amplitude level change that was outside the 95% CI. In CNH, there was no main effect for time [$F(1, 14) = 2.9$; $p = 0.12$] or frequency [$F(7, 8) = 1.85$; $p = 0.18$] in the test ear. No main effect of time [$F(1, 14) = 0.62$; $p = 0.91$] or frequency [$F(7, 8) = 0.77$; $p = 0.41$] was determined in the non-test ear. No significant interaction between time and frequency was noted in the test ear [$F(7, 8) = 1.42$; $p = 0.32$] or non-test ear [$F(7, 8) = 0.98$; $p = 0.54$] in CNH. In ANH, there was no main effect

for time [$F(1, 9) = 0.95$; $p = 0.36$] or frequency [$F(7, 3) = 1.62$; $p = 0.39$] in the test ear. No main effect of time [$F(1, 9) = 0.58$; $p = 0.79$] or frequency [$F(7, 3) = 0.67$; $p = 0.89$] was observed in the non-test ear. No significant interaction was noted in the test ear [$F(7, 3) = 3.30$; $p = 0.18$] or non-test ear [$F(7, 3) = 1.53$; $p = 0.29$] in ANH. These results suggest there was no significant decrease in DPOAE amplitude level at the tested frequencies post-VEMP exposure.

Subjective Questionnaire: None of the subjects [CNH (0/14); ANH (0/10)] reported symptoms consistent with otologic or auditory changes pre-and-post VEMP exposure. One subject (child; age 4) was unable to self-report symptoms pre/post VEMP testing due to difficulty understanding the questions. Parental report confirmed no report of otologic or auditory complaints before or after VEMP testing.

Evaluating c-and oVEMP Parameters in Children and Adults with Normal Hearing

Ocular and Cervical VEMP Testing: Response rates for both c- and oVEMP in CNH (using 120 dB SPL simulation level) and ANH (using 125 dB SPL simulation level) were 100% in the respective test-ear. Mean c- and oVEMP latencies and peak-to-peak amplitudes are shown in Table 4. While no significant mean differences in c-and-oVEMP peak-to-peak amplitudes or n10/p16 latencies were noted between the two groups, CNH had significantly shorter p13/n23 latencies compared to ANH (Table 4).

DISCUSSION

Due to the high stimulus level needed for VEMP testing, concern for increased sound exposure in the ear should be warranted when completing VEMP testing in young children. Therefore, the purpose of the present study was two-fold. The first purpose was to measure peSPLs in children and young adult ear canals using short duration, high intensity, VEMP stimuli (100–125 dB SPL at 500 and 750 Hz). Based on children's smaller ECVs, it was hypothesized that children would have higher peSPL values compared to adults and that a linear relationship between equivalent ECV and peSPL would therefore exist.

Probe microphone measurements from the present study confirmed that CNH have approximately 3 dB higher peSPL values in response to high intensity VEMP stimuli (105–125 dB SPL) compared to ANH. These results are consistent with previous investigations that recorded a 3 dB increase in peSPL values in children compared to adults at low intensity VEMP stimuli (75, 80, and 85 dBnHL) and predicted a similar increase for higher intensities (Thomas et al. 2016). This is suggestive that the amount of sound exposure that a child receives in the ear canal during VEMP testing is not necessarily analogous to that of an adult despite a similar stimulation level.

Factors, such as ECV and ear canal length are believed to contribute to SPL differences observed between children and adults. It is well known that in a closed cavity such as the ear canal, SPL doubles with every halving of volume (Beck, et al., 2009). Feigin et al., 1989 demonstrated an average increase of 4 dB between adults and child ears. In the present study, equivalent ECVs were also significantly smaller in CNH compared to ANH, which is

in agreement with previous reports; Thomas et al. (2016) determined that children with smaller ECVs represented the highest peSPL values in their dataset. We also observed a strong linear relationship between equivalent ECV and peSPL at 500 and 750 Hz. This demonstrates that equivalent ECV derived from diagnostic tympanometry can serve as tool for clinicians performing VEMP testing in children and need to determine an acoustically safe stimulation level.

Using this information, there is controversy on the preferred method for determining safe sound energy exposure levels in medical contexts, specifically with VEMP testing. Previous investigators have utilized industrial guidelines and noise dose recommendations from NIOSH (1998), OSHA and European Unions (2003) to determine sound exposure limits during VEMP testing (Krause et al. 2013; Mattingly et al. 2015; Stromberg et al. 2015; Colebatch & Rosengren 2014; Portnuff et al. 2017). However, these guidelines were developed for adults based on the noise exposure he/she would receive over the course of a 40-hour work life, which is not characteristic of what an individual receives during a single VEMP test. Additionally, the type of noise that these standards and guidelines refer to are reflective of cumulative and continuous broadband noise that is not typical of VEMP stimuli. Adherence to these guidelines is difficult as VEMP stimuli do not meet the criteria of either continuous or impulse noise (Rosengren et al. 2009; Rosengren et al. 2010; Colebatch & Rosengren 2014). Similarly, these regulatory standards are not protective of all individuals; 25% of ears could be susceptible to damage at a lower level (Price 1981).

Nonetheless, Colebatch and Rosengren (2014) suggest individuals performing VEMP testing should consider calculating total sound energy exposure that accounts for stimulus duration and intensity. Total sound energy exposure is calculated using the following formula:

$$\text{intensity (SPL)} - 3 \text{ dB (A-weighting)} + 10 \times \log_{10} (\text{stimulus duration in seconds})$$

with a recommended allowance for total sound energy exposure that should not exceed 132 dB SPL. While this total energy calculation has been reported in literature to be useful for verifying sound exposure during VEMP testing (Mattingly et al. 2015; Portnuff et al. 2017), the calculation is based on a 500 Hz stimulus that is attenuated by 3 dB A-weighting filter. A-weighting is standard weighting of the audible frequencies designed to reflect the response of the human ear to noise that is typically represented of a periodic and broad spectrum of frequencies (ANSI 2013). This is not reflective of a VEMP stimulus, which is a single tone-burst frequency with a short duration. Alternatively, c-weighting is a standard weighting of the audible frequencies commonly used for the measurement of peak SPL, and at 500 Hz, has a weighting of 0 dB (ANSI 2013). Therefore, in efforts to maintain a conservative approach in determining total sound energy, the A-weighting filter was not subtracted from the peSPL intensity to determine total energy exposure (Refer to Table 2).

Our data suggest that if standard VEMP stimuli (125 dB SPL (95 dBnHL) are used, the average child will receive 130 peSPL in the ear during VEMP testing. Using this formula suggests that, on average, children who receive two trials of c-and-oVEMP testing (500 Hz TB; stimulus duration of 2 total seconds; no subtraction of 3 dB for A-weighting) are exceeding the recommended total sound energy limit of 132 dB HL, with total sound energy

equating to 133.01 dB SPL (Colebatch & Rosengren 2014). While it's unclear how well this formula can be used to promote safety in VEMP testing, this encourages awareness that peSPLs are higher in children and caution should be considered prior to presenting adult-like VEMP stimulation levels. Our data suggest that VEMP stimuli be turned down to 120 dB SPL in children whose equivalent ECVs are less than 0.8 mL. Pediatric vestibular testing often recommends the use of VEMP testing in children as young as 2–3 years of age as responses from the saccule and utricle can be reliably recorded (Wang et al. 2012; O'Rielly 2013). While the age range of our subjects was not less than 4 years of age, we hypothesize that stimulus levels may need to be turned down to 115 dB SPL in children whose ECVs are smaller than 0.4 mL.

The present study also evaluated peSPL measurements at 750 Hz for CNH and young ANH. Because higher frequencies have shorter durations, using a 750 Hz TB would further reduce the total energy exposure. Results determined that CNH continued to have significantly higher peSPL values than ANH, however the overall mean ($M=127.9$; $SD=1.1$) and range peSPLs (125.5–130.0) in response to 125 dB SPL were 2 dB less than peSPLs at 500 Hz. This suggests a potential advantage in using 750 Hz TB in children and young adults as an effort to minimize sound exposure in the ear during testing. Welgampola and Colebatch (2001) observed the largest cVEMP amplitudes occurring between 600 and 1000 Hz, with a mean of 700 Hz, suggesting that a 750 Hz TB is an effective stimulus for evoking large VEMP amplitudes and low VEMP thresholds while also minimizing sound exposure.

The second purpose of the present study was to determine the effect of VEMP stimuli on cochlear function. It was hypothesized that with the VEMP stimulus parameters used in the methodology (i.e., shorter duration and lower stimulation level), there would not be significant change in outer hair cell function in CNH and ANH and reliable VEMP responses would still be achieved. We observed no change in audiometric thresholds or DPOAE responses, which support the hypothesis that using a shorter duration and lower stimulation level does not yield significant changes in outer hair cell function post VEMP testing. Previous studies performed in adults (Krause et al. 2013; Mattingly et al. 2015; Stromberg et al. 2016) have reported subjective and objective changes in hearing status following VEMP exposure. However, the VEMP stimulus parameters were diverse in these investigations and included an increased number of stimuli (e.g., up to 800 stimuli) and longer stimulus durations (e.g., 10 msec), and thus delivering a higher total noise exposure compared to the stimuli used in the present study. Stimulus duration, number of repetitions, and stimulation level are parameters in VEMP testing that can affect the overall SPL delivered to the individual's ear (Portnuff et al. 2017). Colebatch and Rosengren (2014) advocate that total sound exposure can be minimized by lessening the duration of each stimulus and performing VEMP testing at a lower stimulation level (Welgampola & Colebatch, 2001). Therefore, it is plausible that the increased duration and number of repetitions, increased the total energy exposure in these respective studies and could have contributed to the observed shift in DPOAE amplitude levels.

This is the first report to document c- and oVEMP responses in children with normal hearing using a lower stimulation level than what is commonly practiced in adult testing (125 dB SPL; 94 dBnHL) (Piker et al. 2015; Portnuff et al. 2017). In our study, reliable c- and

oVEMP responses were produced in 100% of CNH using 120 dB SPL (89 dBnHL), suggesting that in younger populations, a lower stimulation level will lead to safe noise exposure without sacrificing clinical diagnostic ability. Previous reports evaluating optimum stimulus parameters for tone burst-evoked VEMP responses also recommend that a stimulation level of 120 dB SPL be used as multiple repetitions of each stimuli may be needed and energy exposure should be considered (Welgampola & Colebatch 2001). While the number of repetitions used in this study remained constant (2 repetitions for c- and oVEMP), it is likely that the number of repetitions and stimuli will vary for pediatric testing in a clinical setting. During VEMP testing, younger children ages (3–6 years) reported difficulty maintaining head elevation or eye gaze for sufficient muscle contraction, and subsequent trials were needed to replicate responses (Kelsh et al. 2006).

In the instance of utilizing EMG monitoring to normalize amplitude data during cVEMP testing, additional stimuli may also be delivered to the ear if muscle contraction is not sufficient based on predetermined EMG filter settings (Colebatch & Halmagyi 1992; Colebatch et al. 1994; Akin et al. 2004). In the current study, EMG signals were monitored to maintain background muscle activity from 100–300 μ V. In some instances, more stimuli were delivered to the ear if SCM muscle activity was not within this range, thereby increasing total energy exposure. To assess this issue, the number of stimuli that was delivered to the ear but rejected by the VEMP system was recorded for all subjects. As expected, there were no rejected stimuli found during oVEMP testing, as EMG monitoring was not performed. For the ANH, the average number of rejected stimuli during cVEMP testing was 8 with a maximum of 14 rejects for two repetitions. When using a 125 dB SPL stimulation level, the total amount of sound energy exposure the average adult in our study received would have been 128.08 dB, with a maximum of 128.13 dB. For CNH, the average number of stimuli rejected for a given subject was 16 for two repetitions of cVEMP, with a maximum of 54 rejects for one subject. Using 120 dB SPL as a stimulation level and accounting for the 3 dB increase in peSPL in children, the resulting sound exposure levels were 126.15 dB for the average child, and 126.46 dB for the subject that received 54 additional stimuli. These results suggest that when accounting for additional stimuli secondary to EMG monitoring, the sound energy exposure is still under the 132 dB recommended allowance. The absence of change in the hearing threshold and DPOAE data pre- to post-VEMP observed for both groups supports that the additional amount of exposure was not significant.

Alternatively, it is possible that the range of additional stimuli could be more than what was observed or accumulate over several trials. Using the same stimulus parameters and calculation discussed in this study, the maximum amount of c- or oVEMP stimuli that an examiner could safely present would be 1,250 for individuals with equivalent ECV > 0.8 mL at 125 dB SPL stimulation level or 1,950 stimuli for persons with equivalent ECV < 0.8 mL at 120 dB SPL stimulation level, with the additive 3 dB, suggesting that there is headroom for additional rejected stimuli or additional full trials before exceeding the recommended 132 dB allowance. Due to variability that can occur during VEMP testing, further strategies to minimize sound exposure should also be considered (e.g., reduce number of stimuli, shorten stimulus duration, lower stimulation level).

Peak-to-peak amplitude responses for c- and oVEMP in this study were consistent with previous normative data collected in children using air-conduction VEMP stimuli at 123–127 dB SPL (Hsu et al. 2009; Wang et al. 2012) and young adults (Welgampola & Colebatch 2001; Hsu et al. 2009; Janky & Shepard 2009). Reduced cVEMP amplitudes are more frequently reported with age (Welgampola & Colebatch 2001; Su et al. 2004; Basta et al. 2007; Janky & Shepard 2009); the age range of the study participants did not range widely (child; $n=16$; age range 4–12) to expect age-related reductions in cVEMP amplitudes, as most pronounced changes occur after age 60 (Welgampola & Colebatch, 2001; Su et al. 2004; Basta et al. 2007; Janky & Shepard 2009). The larger amplitudes measured in children could be related to the inverse relationship of subcutaneous muscle thickness to raw amplitude, as described by Chang et al. (2007).

In our results, cVEMP p13 and n23 latencies were significantly shorter in CNH compared to ANH. The earlier appearance of latency values in pediatric populations was previously reported by Sheykholesami et al. (2005), Kelsch et al. (2006), and Valente (2007) and could be explained by structural differences such as neck length and head size, or by differences in conduction velocities or immature inhibition of the reflex pathways (Sheykholesami et al. 2005; Chang et al. 2007; Zagólski 2007). cVEMP n23 latency has been found to increase with age (Welgampola & Colebatch 2001; Su et al. 2004; Kelsch et al. 2006; Maes et al. 2014); however, this finding has not been reported consistently (Basta et al. 2005). Disagreement among reported findings may be related to differences in recording techniques such as variations in stimuli, rise / fall and filter settings. With regards to oVEMP, no differences were noted between CNH and ANH. Wang et al. (2013) reported reliable oVEMP responses emerge after age 2 in children and do not correlate to age, suggesting there are no continued maturation effects (Welgampola & Colebatch 2001; Su et al. 2004; Chang et al. 2007; Maes et al. 2010).

CONCLUSION

These findings demonstrate the importance of understanding the relationship between VEMP stimulus parameters and amount of sound energy exposure delivered to children's ears. A common assumption is that acoustic trauma is not anticipated following VEMP testing as the amount of sound energy is not enough to permanently affect cochlear function. However, here we report significantly higher (~ 3 dB) peSPL measurements in children and adults at using common high intensity VEMP stimuli. This evidence suggests that children, especially those with smaller than 0.8 mL ECV, do not receive the same amount of sound pressure in the ear canal during VEMP testing compared to adults and may be at risk for unsafe sound energy exposure during testing. Given differences in children compared to adults, consideration should be given to minimize the risk of acoustic trauma secondary to VEMP; specific attention should be made to evaluate stimulus parameters that affect total sound pressure level (e.g., stimulus duration, stimulation level, number of stimuli presented). To further minimize sound energy exposure during VEMP testing in children, further studies investigating frequency tuning in children are underway.

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Figure 1. Relationship between equivalent ear canal volume (ECV) and peak-to-peak-equivalent sound pressure level (peSPL) in response to (A) 500 TB and (B) 750 TB stimuli at 125 dB SPL stimulation level in children and adults with normal hearing

Line in each graph represents regression line through the data.

Figure 2. Mean audiometric thresholds for children with normal hearing (A) and adults with normal hearing (B)
 Black-line represents pre-VEMP thresholds and blue-line represents post- VEMP thresholds.

Table 1

Mean (SD), Range, and Mean Difference of Peak-to Peak Equivalent SPL (peSPLs) for Children and Adults in Response to 105, 110, 115, 120, and 125 dB SPL at 500 and 750 Hz Tone Burst (TB) Stimuli.

Stimuli	Child			Adult		
	Mean (SD)	Range	Mean (SD)	Range	Mean Difference	
500 Hz TB: 105 dB SPL	110.2 (1.8)	107.7–114.7	107.4 (1.4)	105.2–109.7	2.8	
500 Hz TB: 110 dB SPL	115.7 (2.0)	113.1–120.0	112.8 (1.4)	110.5–114.9	2.9	
500 Hz TB: 115 dB SPL	120.8 (1.9)	118.0–125.3	118.1 (1.3)	115.8–120.1	2.7	
500 Hz TB: 120 dB SPL	125.9 (2.0)	122.7–130.3	123.1 (1.3)	120.8–125.1	2.8	
500 Hz TB: 125 dB SPL	130.0 (1.7)	126.4–131.8	127.4 (1.3)	125.2–129.3	2.6	
750 Hz TB: 105 dB SPL	107.5 (1.3)	105.1–109.7	105.1 (1.2)	102.9–107.1	2.4	
750 Hz TB: 110 dB SPL	112.8 (1.3)	110.2–114.8	110.4 (1.2)	108.2–112.3	2.4	
750 Hz TB: 115 dB SPL	118.1 (1.3)	115.5–120.0	115.7 (1.2)	113.4–117.5	2.4	
750 Hz TB: 120 dB SPL	123.2 (1.3)	120.7–125.2	120.8 (1.2)	118.6–122.7	2.4	
750 Hz TB: 125 dB SPL	127.9 (1.3)	125.5–130.0	125.7 (1.1)	123.4–127.4	2.2	

Table 2

Effect of Equivalent Ear Canal Volume (ECV) on Total Energy Exposure in Children and Adults in Response to 500 Hz Tone Burst Stimuli.

Range of ECV (mL)	Range of peSPL	Total Energy Exposure (dB SPL)
0.2–0.8	138.95 – 132.51	139.00 – 132.51
0.9 and +	131.90 – 131.30	131.90 – 131.30

Dark grey= considered unsafe total energy exposure (> 132 dB); White= considered safe total energy exposure. Stimulus parameters: dBA weighting not factored into equation (see discussion); duration= 4 msec; number of stimuli= 500 (200 cVEMP stimuli; 300 oVEMP stimuli).

Table 3

Pre-VEMP DPOAE Test-Retest 95% Confidence Intervals for Children and Adults and DPOAE Level Mean Difference Between Pre and Post-VEMP testing.

Frequency	Child		Adult	
	95% CI	Pre-Post DPOAE Level Difference	95% CI	Pre-Post DPOAE Level Difference
750 Hz	-2.6 to 2.5	0.2	-2.8 to 2.1	1.0
1000 Hz	-2.8 to 1.8	-0.4	-2.1 to 2.1	1.0
1500 Hz	-3.8 to 2.6	-0.4	-1.0 to 2.7	0.1
2000 Hz	-2.4 to 3.9	0.5	-2.2 to 3.7	0.7
3000 Hz	-3.4 to 2.7	0.4	-2.8 to 1.2	-0.12
4000 Hz	-2.0 to 3.6	1.7	-1.7 to 2.1	-1.0
6000 Hz	-2.7 to 3.1	0.6	-1.7 to 2.1	0.4
8000 Hz	-2.0 to 3.3	0.7	-2.0 to 1.9	-0.2

DPOAE, distortion product otoacoustic emissions; VEMP, vestibular evoked myogenic potentials.

Table 4

Cervical and Ocular VEMP Mean (SD) Latencies and Peak-to-Peak Amplitudes for Children and Adults in Response to 500 Hz Tone Burst Stimuli.

	VEMP Outcome Parameter	Child Mean (SD)	Adult Mean (SD)	Significance <i>p</i> -value
Cervical VEMP	p13 Latency (msec)	13.23 (0.87)	14.83 (1.27)	0.003
	n23 Latency (msec)	20.94 (1.77)	22.94 (1.15)	0.002
	Peak-to-Peak Amplitude (uV)	268.85 (210.12)	238.88 (118.60)	0.69
Ocular VEMP	n10 Latency (msec)	10.20 (0.72)	10.73 (0.48)	0.66
	p16 Latency (msec)	14.52 (1.82)	15.24 (0.84)	0.19
	Peak-to-Peak Amplitude (uV)	6.62 (2.51)	9.38 (5.53)	0.17

* Student t-test with Welch correction factor: Significant difference between children and adults.

Bold values represent significance. VEMP, vestibular evoked myogenic potentials.