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Safe Use of Acoustic Vestibular-Evoked Myogenic Potential Stimuli: Protocol and Patient-Specific Considerations

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Abstract

Background: Vestibular-evoked myogenic potentials (VEMPs) are commonly used clinical assessments for patients with complaints of dizziness. However, relatively high air-conducted stimuli are required to elicit the VEMP, and ultimately may compromise safe noise exposure limits. Recently, research has reported the potential for noise-induced hearing loss (NIHL) from VEMP stimulus exposure through studies of reduced otoacoustic emission levels after VEMP testing, as well as a recent case study showing permanent sensorineural hearing loss associated with VEMP exposure.

Purpose: The purpose of this report is to review the potential for hazardous noise exposure from VEMP stimuli and to suggest clinical parameters for safe VEMP testing.

Research Design: Literature review with presentation of clinical guidelines and a clinical tool for estimating noise exposure.

Results: The literature surrounding VEMP stimulus-induced hearing loss is reviewed, including several cases of overexposure. The article then presents a clinical calculation tool for the estimation of a patient's safe noise exposure from VEMP stimuli, considering stimulus parameters, and includes a discussion of how varying stimulus parameters affect a patient's noise exposure. Finally, recommendations are provided for recognizing and managing specific patient populations who may be at higher risk for NIHL from VEMP stimulus exposure. A sample protocol is provided that allows for safe noise exposure.

Conclusions: VEMP stimuli have the potential to cause NIHL due to high sound exposure levels. However, with proper safety protocols in place, clinicians may reduce or eliminate this risk to their patients. Use of the tools provided, including the noise exposure calculation tool and sample protocols, may help clinicians to understand and ensure safe use of VEMP stimuli.

Key Words: noise-induced hearing loss, otolith testing, saccule, utricle, VEMP protocol, VEMP safety, vestibular-evoked myogenic potential

Abbreviations: cVEMP = cervical vestibular-evoked myogenic potential; DPOAE = distortion product otoacoustic emission; DRC = damage-risk criterion/criteria; EU = European Union; nHL = normalized hearing level; NIHL = noise-induced hearing loss; NIOSH = National Institute for Occupational Safety and Health; oVEMP = ocular vestibular-evoked myogenic potential; peSPL = peak-equivalent sound pressure level; pSPL = peak sound pressure level; REL = recommended exposure level; SSCD = superior semicircular canal dehiscence; VEMP = vestibular-evoked myogenic potential

BACKGROUND

Vestibular-evoked myogenic potentials (VEMPs) are used to electrophysiologically evaluate the function of the saccular and utricular reflex pathways. The sacculo-collic reflex pathway originates in the saccule and inferior vestibular nerve and is recorded from the tonically contracted sternocleidomastoid muscle as the cervical vestibular-evoked myogenic potential (cVEMP) (Colebatch et al, 1994). The utriculo-ocular

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reflex pathway presumably originates in the utricle and superior vestibular nerve and is recorded from the contralateral inferior oblique orbital muscle as the ocular vestibular-evoked myogenic potential (oVEMP) (Curthoys et al, 2011; Kantner and Gürkov, 2012). Performing both VEMP recordings provides a clinically viable method for evaluation of otolith end organs and subsequent superior and inferior vestibular nerve branches. VEMPs are commonly applied in the clinical assessments of patients suspected with peripheral vestibular dysfunction such as in acute vestibular neuritis (Lin and Young, 2011; Walther and Blödow, 2013; Adamec et al, 2014), Meniere's disease (Kingma and Wit, 2011; Sandhu et al, 2012; Taylor et al, 2012), and superior semicircular canal dehiscence (SSCD) (Minor, 2005; Janky et al, 2013), as well as in neurological conditions such as vestibular migraine (Gozke et al, 2010; Hong et al, 2011; Zaleski et al, 2015) and multiple sclerosis (Gabelić et al, 2013; Güven et al, 2014).

VEMPs can be recorded using several types of stimuli, including air-conducted sound, bone-conducted vibration (Welgampola et al, 2003; Basta et al, 2005; Miyamoto et al, 2006), or electrical stimulation (Cheng et al, 2008; Chang et al, 2013), but air-conducted stimulation is presumed to be the most widely used in the clinical setting due to the expense of adding additional equipment for other methods (Felipe and Kingma, 2014). VEMPs can be reliably elicited with short-duration tone bursts or clicks. Due to frequency tuning within the stimulus pathway, 500-Hz tone bursts are described as the most effective stimulus, as they produce large amplitude responses at lower thresholds (Rosengren et al, 2009). High-intensity stimuli are used to elicit the VEMP, typically between 120 and 140 dB pSPL, reaching the upper limit of what is considered safe exposure (OSHA, 1981; Price, 1981; NIOSH, 1998; Krause et al, 2013; Mattingly et al, 2015). Table 1 provides a sample of current published stimulus parameters and guidelines for cVEMP. Ocular VEMP stimulus parameters are generally similar to those used for cVEMP responses (Wang et al, 2009; Murnane et al, 2011).

Several studies have investigated the potential adverse effects of VEMP testing on cochlear function (Krause et al, 2013; Mattingly et al, 2015; Stromberg et al, 2016). Krause et al (2013) measured cochlear function using distortion product otoacoustic emissions (DPOAE) before and after standard cVEMP testing (500-Hz tone burst, 133 dB SPL, no measurement in peak sound pressure level [pSPL] provided) and audiometry 24 hr following VEMP exposure. While the authors described no significant threshold shifts in the postexposure audiometry, they noted a significant decrease (0.5–3 dB) in DPOAE levels from 4000 to 6000 Hz after exposure, which was greater in those with subjective complaints of hearing symptoms. Stromberg et al (2016) focused their investigation on the effect of repeated low-frequency (500 Hz, 130 dB peSPL) tone-burst cVEMP stimulation by measuring DPOAEs at 750 and 3000 Hz, as well as pre/postexposure audiometry. The authors found a significant reduction in DPOAEs at 750 Hz (0.5–1.35 dB) and at 3000 Hz (1.6–2.1 dB) after exposure. Consistent with Krause et al (2013), Stromberg et al (2016) did not find significant reduction in measurable hearing thresholds after exposure but found a reduction in DPOAE amplitude over a larger range of frequencies. Stromberg et al (2016) found a DPOAE reduction (2.1 dB) following cVEMP evaluation that was equivalent to half the reduction caused by exposure to

Table 1. Sample Published cVEMP Stimulus Parameters and Guidelines

Article	Papathanasiou et al (2014)	British Society of Audiology (2012)	Piker et al (2015)	Krause et al (2013)	Janky and Shepard (2009)
Article type	Guideline	Guideline	Research article	Research article	Research article
Stimulus					
Type	Tone burst or 0.1-msec click	Tone burst	Tone burst	Tone burst	Tone burst or 0.1-msec click
Frequency	400–600 Hz	500 Hz	500 Hz	500 Hz	250–1000 Hz
Duration	≤7 msec	2:1:2 (5 msec)	2:0:2 (4 msec)	10 msec	2:0:2 (4 msec)
Gating	—	Blackman	Blackman	Hanning	Blackman
Recording parameters					
Gain	5,000×	—	5,000×	—	—
Rate	5/sec (2–10 Hz)	4.9–5.1/sec	5/sec	3.333/sec	13.3/sec
Intensity	120–135 dB pSPL (maximum 140 dB pSPL)	95–100 dB nHL	125 dB pSPL	133 dB SPL	Tone burst: 123 dB SPL; click: 119 dB SPL
Filters	5–30 Hz	10–1000 Hz	10–1500 Hz	—	20–1500 Hz
Window	100 msec	80 msec	100 msec	—	100 msec
Sweeps	100–250	100–150	≥80	200	200

the maximally allowed occupational noise for an 8-hr work day as reported by Reuter et al (2007) and Aranda de Toro et al (2010). Most recently, Mattingly et al (2015) report a case study of sudden permanent bilateral sensorineural hearing loss after cVEMP and oVEMP testing with stimulation intensities ranging between 128 and 135 dB pSPL. The authors expressed concern for stimulus level, duration, total sound exposure with multiple trials, and the individual's susceptibility to acoustic trauma. Of note, the authors from these studies vary in their report of stimulus output (e.g., dB pSPL versus dB peSPL). Comparisons among these studies should be carefully considered, as pSPL and peak-equivalent sound pressure level (peSPL) are different references and could result in different dB SPL values (Burkard, 1984; IEC, 2007; see below section "How Are VEMP Intensity Levels Measured?" for details).

These investigations into VEMP stimulus exposure demonstrate the necessity to safely measure VEMP responses without affecting cochlear function. As noted by the concerns of Mattingly and colleagues (2015), extended stimulus intensity, duration, and repetition resulting in increased overall exposure levels may need careful consideration. Because previous research regarding changes in cochlear function following VEMP testing has been limited to individuals with normal hearing, our current understanding of the potential consequences for individuals susceptible to noise exposure should also be considered.

When evaluating sound exposure from VEMPs, both instantaneous noise levels and the actual exposure measured over time must be considered. If the output levels of a device exceed the recommended exposure level (REL) for a specified damage-risk criterion (DRC), the exposed individual could be at risk for hearing loss. While several DRC exist for industrial noise exposure across the world, there is no specific DRC established for patient noise exposure in a healthcare setting. Given this, industrial noise exposure standards will provide the structure for this discussion. Risk of hearing loss will reference the DRC established by the US National Institute for Occupational Safety and Health (NIOSH, 1998) and the more conservative standard promulgated by the European Union (EU, 2003). The NIOSH REL is set at a maximum 8-hr exposure of 85 dBA, while the EU REL is 80 dBA. Both standards use a 3-dB time-intensity trading ratio (exchange rate), which represents the increment of decibels that result in a halving of exposure time. Using the DRC, an individual's exposure can be represented as a noise dose, where a 100% noise dose is equivalent to an 8-hr exposure at the REL. Noise dose is a cumulative measure, and exposures from individual activities in a given day are added together to calculate a total noise dose. Noise doses exceeding 100% would generally be considered to place the exposed individual at a higher than normal risk for acquiring hearing loss. Both the NIOSH and EU DRC set upper limits of 140 dBC for impulsive noises (sounds lasting <1 sec).

The published DRC limits for impulsive noises were developed to prevent hearing loss in the majority of workers and are not protective of 100% of individuals (Ward et al, 1961; Price, 1981; Committee on Hearing and Bio-Acoustics, 1992). Specifically, Price (1981) suggests that the critical level for instantaneous damage occurs at 140 dB pSPL for an ear at the 25th percentile of susceptibility (i.e., 75% of ears would not be at risk for sudden damage at 140 dB SPL). However, Price (1981) further notes that an ear in the fifth percentile for noise sensitivity is susceptible to instantaneous hearing loss with exposures at 132 dB SPL, suggesting that a small percentage of ears would incur sudden trauma from this lower level. Thus, the regulatory standards restricting exposure to no more than 140 dBC are not protective of all individuals.

HOW ARE VEMP INTENSITY LEVELS MEASURED?

The fundamental key to ensuring safe use of high-level stimuli for VEMP testing is understanding the individual patient's overall sound exposure from the test. First, to understand exposure, the clinician must have an accurate understanding of the actual output level of their clinical equipment. VEMP equipment should be calibrated by measuring either pSPL or peSPL in accordance with IEC (2007). Measurements in dB SPL for transient stimuli reflect some degree of averaging—either averages of multiple stimuli over time or root-mean-square averages of a specific stimulus token. These types of averages do not reflect instantaneous peaks in the stimulus. The threshold of a VEMP response reflects response of the saccule and utricle to the "peak intensity" of the stimulus, which may not be reflected well in the dB SPL reference. Furthermore, when considering the risk for acoustic trauma, the peak of the stimulus intensity is the metric of interest. In short, a sound-level meter must be able to measure the peak of the stimulus, which occurs very rapidly. Measurements using a sound-level meter set to a "fast response" will average sound levels measured over a given time (e.g., 125 msec), and will result in measured levels which are $\sim$6 dB below the actual peak of the signal for 500- or 1000-Hz tone bursts (Beattie and Rochverger, 2001). Some sound-level meters are capable of measuring transients using a "peak hold" type of response to obtain a pSPL measurement. Otherwise, pSPL can be measured using a microphone, preamplifier, and conditioning amplifier, then viewing the absolute greatest amplitude of the signal on an oscilloscope. peSPL is derived from adjusting the level of the output until equivalent to the peak-to-peak or baseline-to-peak

amplitude or voltage of the transient. Of note, pSPL is typically 3+ dB greater than peSPL, depending on which peSPL value is used (Burkard, 1984; Laukli and Burkard, 2015).

Furthermore, signal output may be described using dB HL or dB normalized hearing level (nHL) as the reference. Due to the known variations in human hearing, these references create a normalized value across frequencies. Converting dB nHL or dB HL to dB pSPL or dB peSPL requires knowledge of the correction factor used for that specific test frequency. This can often be obtained from the manufacturer or during equipment calibration. Clinicians should become familiar with their equipment-specific calibration methods and the derivation of peak output. Once the output level in pSPL or peSPL is known, the exposure can be estimated by entering the overall exposure time and exposure level into the calculation for a given DRC, including necessary weighting filters for that DRC. When assessing risk for acoustic trauma from a stimulus, output levels in pSPL or peSPL should be used. Additionally, knowing the output levels in pSPL or peSPL allows comparisons that are more accurate among laboratories and in the reported literature.

Individual-specific ear canal volume should be considered when calculating exposure level. In a closed cavity, sound pressure level doubles with every halving of volume (Beck et al, 2009) and will affect the actual output level. For instance, a decrease in ear canal volume from 2 to 1 cc would cause an increase in stimulus level of 6 dB. Real-ear-to-coupler differences also provide some evidence of individual canal differences on sound pressure level. For example, Feigin et al (1989) demonstrated an average increase of 5 dB between adult and pediatric ears, as well as a systematic decrease in real-ear-to-coupler differences with age. For these reasons, we recommend considering ear canal volume when calculating exposure level.

HOW CAN WE SAFELY TEST VEMPS?

What Is Your VEMP Stimulus Intensity?

It is the responsibility of clinicians to understand the output levels produced by their calibrated equipment and to calculate the exposure for each individual patient. Equipment should be calibrated in dB peSPL or pSPL to compare accurately to published DRCs. If equipment output is provided in either dB nHL or dB HL, clinicians should know their equipment-specific conversion factor between those values and dB p/peSPL. It is important to note that calibrations may vary between sites and between equipment. For example, a 95-dB nHL stimulus may be equivalent to 126 dB peSPL in one laboratory, but 122 dB peSPL in another, likely leading to different outcomes. When producing a report for clinical or research use, the clinician should present their VEMP tracings accompanied by their measured VEMP levels in dB p/peSPL. Reporting in dB p/peSPL allows VEMP results to be compared to previous or future tests and to be repeated by outside clinicians or researchers.

Clinicians should also consider the possible medicolegal liability associated with VEMP stimuli. An audiologist should be able to calculate overall VEMP exposure and be able to demonstrate that the patient's stimulus exposure was safe. To lessen medicolegal liability, clinics should develop consistent protocols and maintain calculations of exposure on file to present to authorities or in legal proceedings if claims of VEMP-induced hearing loss arise. For each patient, comprehensive records of all VEMP stimuli used should be maintained.

How Can Safe Exposure Levels Be Maintained?

The clinician should monitor the patient's sound exposure to ensure that safe exposure to VEMP stimuli is maintained. For conservative protocols, total noise doses should not exceed 100% of the NIOSH noise dose, instantaneous sounds should not exceed 132 dB pSPL, and total energy should remain below 132 dB SPL over 1 sec. Exceeding these limits increases the risk of incurring noise-induced hearing loss (NIHL) in highly susceptible individuals (Price, 1981). A significantly more conservative protocol could follow the EU DRC, though this has the potential to limit the clinical utility of some VEMP testing.

Clinicians should first take into consideration if a patient is at risk for excessive noise exposure during VEMP testing. For example, a patient may belong to a specific population with a higher than average risk for hearing loss from noise exposure (see following section "Should VEMP Testing Be Modified for Certain Populations?" for details), or an individual may have already exceeded his or her daily recommended noise limits before testing. Patients with a higher than normal risk for NIHL from VEMP stimuli may be poor candidates for VEMP testing. Clinicians should further consider the strategies in Table 2 to maintain exposure below the recommended total energy levels. Most

Table 2. Summary of Strategies to Reduce VEMP Noise Exposure

- Minimize number of sweeps
- Minimize number of repetitions
- Minimize stimulus duration
- Limit search for threshold to necessary cases (e.g., SSCD)
- Consider starting at a lower intensity level
- Consider the patient's total daily noise exposure in addition to VEMP exposure

simply, reducing stimulus duration and/or the total number of stimuli presented will diminish the patient's total sound exposure. Minimal stimuli are needed, especially for reliable recording of VEMP responses. Additionally, a small reduction in maximum intensity will reduce a patient's exposure significantly. For example, with the same number of stimuli, a reduction of 3 dB will reduce a patient's overall dose by half. Often this small reduction in intensity may not significantly affect the diagnostic utility of the VEMP data.

Table 3 shows an example of how noise dose changes with increasing total exposure time. The stimulus level, duration, and number of sweeps are constant, but the number of trials is increased. For fewer repetitions, this protocol remains within appropriate exposure limits according to all noise dose calculations. With increased number of repetitions, this protocol can provide a substantially high noise dose. While it would be uncommon to conduct eight repetitions of 150 sweeps for cVEMP recording alone, this exposure could be obtained when evaluating both cVEMP and oVEMP.

Should VEMP Testing Be Modified for Certain Populations?

Clinicians should weigh what information is necessary for obtaining a proper diagnosis of vestibular dysfunction, especially for patients who may require more caution (Table 4). For example, if a clinician is suspicious of third-window disorder in a patient (e.g., SSCD), searching for a VEMP threshold may be of significant diagnostic utility. In this case, the clinician assessing for a third-window disorder should start a VEMP threshold search at a relatively low level, as VEMPs within this population may demonstrate abnormally low VEMP threshold (Minor, 2005). Alternatively, if the clinical question is generally assessing saccular or utricular function, measuring the presence of the VEMP response within normative limits may be adequate and searching for a threshold at 85 or 90 dB nHL may not be necessary. Likewise, if a VEMP response is absent at a level associated with typical function, there may be no clinical utility in documenting the presence or absence of a response at a higher intensity level.

The diagnostic utility of VEMPs also varies depending on the population and the need for otolith reflex-specific information. Attempting to obtain VEMPs may not be worth the added exposure risk within certain patient populations. For example, attempting to obtain VEMPs on elderly patients may not be worth the added risk, as the likelihood of bilaterally absent VEMP responses to air-conducted stimuli significantly increases with age >70 yr (Piker et al, 2015). Conversely, for patients receiving vestibular evaluation before cochlear implant surgery, it may be valuable to increase VEMP levels to near maximum output to assess the status of the preoperative vestibular system. The clinician should judge whether high-intensity VEMPs will provide meaningful clinical information for the appropriate management of the patient.

What about the Patient with Additional Daily Noise Exposure?

While the clinician can control the noise dose acquired during VEMP testing, the overall daily noise exposure should also be considered. As noise dose is cumulative across all activities in a patient's day, it may be important to avoid additional sound exposure for some patients. For example, patients who work in a noisy environment may have received all or part of their noise dose in the workplace, or may be receiving additional medical testing that exposes them to noise (e.g., magnetic resonance imaging). The diagnostic need for VEMP testing should be considered in this patient and the risks weighed against the benefits before testing. Conversely, patients should remain isolated from noise before the testing, and, depending on the dose accrued from the VEMP testing, may need to advise patients to remain isolated from noise following the testing.

What Patient Populations May Need Special Consideration?

Certain populations of individuals may be at higher risk for NIHL from VEMP noise exposure, including children, those with tinnitus or hyperacusis, and those with third-window phenomena (Table 4). Consideration

Table 3. Example of the Effect of Stimulus Parameters on Noise Dose

Number of Trials	Total Exposure Time (msec)	Total NIOSH Dose (%)	Total EU Dose (%)	Total Energy (dB >1 sec)
2	800	18.06	57.34	122.03
4	1,600	36.12	114.68	125.04
6	2,400	54.18	172.02	126.80
8	4,800	108.37	344.04	129.81

Note: The number of trials is varied while holding the remaining stimulus parameters constant (stimulus parameters held constant: intensity = 126 dB peSPL, duration = 4 msec, number of sweeps per trial = 150).

Table 4. Special Considerations for Lower VEMP Stimulus Levels

- History of tinnitus
- Hyperacusis
- Known susceptibility to noise exposure (e.g., existing NIHL)
- Third-window phenomenon (e.g., SSCD, large vestibular aqueduct)
- Pediatrics
- Current/recent use of ototoxic agents (e.g., platinum chemotherapy, antibiotics)

should be given to their exposure from VEMP stimuli to maintain safe exposure levels.

Children

Young children are often evaluated with VEMP testing due to ease of administration in this population. Numerous pediatric studies have been completed evaluating children as young as a few days of age using VEMP testing. In studies evaluating the youngest patients, adult-like stimuli have consistently been used with success (e.g., Sheykholeslami et al, 2005; Chen et al, 2007; Erbek et al, 2007). However, when evaluating children, VEMP stimuli may not need to be presented using adult stimulus levels. Maes et al (2010) provide normative data for children aged 4–12 yr, noting consistently present VEMP responses at ~120 dB SPL (84 dB nHL). In younger populations, a protocol using a lower intensity level will lead to safer noise exposure without sacrificing clinical diagnostic ability.

Ear canal volume may be another consideration, especially when testing the pediatric population. The absolute forward pressure does not change for a 500-Hz VEMP stimulus at the level of the tympanic membrane for pediatric ears (Okabe et al, 1988; Abdala and Keefe, 2012), but for every halving of volume in the ear canal, there is a doubling of sound pressure based on 2-cc coupler measurements. This estimate is conservative, but measuring ear canal volume before VEMP testing would allow for adjusting maximum output levels to accommodate for this change (e.g., −6 dB for 1.0 cc, −12 dB for 0.5 cc). Additionally, clinicians should be aware of the size of the coupler used for VEMP equipment calibration. Table 5 shows the theoretical impact of a change in ear canal volume on noise dose. Note the significant change in noise dose and total energy with decreasing ear canal volume.

There is also evidence of the potential for greater NIHL from high noise exposure in children. While no human data are available, some data in animal models suggest that young auditory pathways may be more susceptible to cochlear and retrocochlear noise effects. Kujawa and Liberman (2006) found that young mice had substantially more primary neural degeneration through the cochlea when exposed to high noise levels compared to older mice. These changes rendered the young mice at higher risk of greater age-related hearing loss later in life. Though no specific human research has investigated this contention, these mouse model data warrant taking specific care when exposing children to VEMP noise. Fortunately, because children generally demonstrate robust VEMP responses, high stimulus levels may not be needed.

Patients with Tinnitus or Hyperacusis

Specific care should be taken when considering VEMP testing on patients with persistent, bothersome tinnitus or hyperacusis. Though there is essentially no literature using VEMP studies in patients with tinnitus, the authors' clinical experience has shown that patients with tinnitus may experience an increase in their tinnitus perception during VEMP testing. Furthermore, as the severity of NIHL appears to be correlated with the severity of tinnitus, clinicians should avoid any increased risk of exacerbating or incurring NIHL in patients (Mazurek et al, 2010). Patients with reactive tinnitus (tinnitus known to be louder during high noise exposure) may be at particular risk of experiencing discomfort from VEMP testing. With limited exposure, this is likely to be only temporary. If a patient reports new sudden-onset tinnitus during VEMP testing, the test should be immediately discontinued.

Patients who report hyperacusis (abnormal sensitivity to sound) may not be comfortable with VEMP stimuli for the duration of the test. When a patient with hyperacusis presents for a vestibular evaluation, VEMP testing should be considered only in cases where it is necessary for diagnosis, such as in a case of suspected superior canal dehiscence (Modugno and Brandolini, 2014; Monroe and Sinks, 2014). When VEMP testing is necessary, an altered protocol should always be considered, using a lower intensity

Table 5. Example of the Theoretical Effect of Ear Canal Volume on Noise Dose

Ear Canal Volume (cc)	Estimated dB SPL	Total NIOSH Dose (%)	Total EU Dose (%)	Total Energy (dB >1 sec)
2	126	13.55	43.01	120.78
1	132	54.18	172.02	126.78
0.5	138	216.73	688.08	132.78

Notes: Decreased ear canal volume results in increased sound pressure, which changes the resulting noise dose. All other stimulus parameters are held constant (stimulus parameters held constant: duration = 4 msec, number of sweeps per calculation = 150).

stimulus to demonstrate presence of the otolith reflex response, perhaps without stimulating at the maximum intensity level commonly used for amplitude and amplitude asymmetry comparisons. If VEMP testing must proceed in a patient with hyperacusis, the patient should be counseled about the risk of discomfort. Patients with phonophobia or misophonia (psychological conditions involving fear or hatred of sound) may be wholly unwilling to participate in VEMP testing.

Patients with Third-Window Phenomena

One form of third-window phenomena is SSCD, an abnormal opening in the osseous roof of the superior semicircular canal, which creates a window into the middle cranial fossa. Typically, acoustically induced changes in intralabyrinthine pressure travel down the cochlear partition and are released at the round window. With SSCD, it is hypothesized that intralabyrinthine pressure may be released through the dehiscence, acoustically stimulating vestibular structures and provoking dizziness (Tullio phenomenon). The altered dynamic of fluid pressure results in the "third-window phenomenon," where air-conducted sound is shunted through the dehiscence. Previous evidence suggests that ears with SSCD have VEMP thresholds that are ~20 dB lower and interpeak amplitudes considerably larger than ears unaffected by SSCD (Sheykholeslami et al, 2004; Zhou et al, 2007; Welgampola et al, 2008; Zhou and Gopen, 2011; Milojcic et al, 2013). For this reason, the stimulus intensity level for VEMP testing in patients who are suspected to have SSCD may be started at a lower level to determine threshold. Using a lower intensity level will avoid any unnecessary patient discomfort and the potential for overdriving the acoustic signal to the inner ear through the dehiscence.

Patients with High Susceptibility to NIHL

Though clinicians have no direct diagnostic test to evaluate susceptibility to NIHL, susceptibility may be inferred in several cases. Patients with existing NIHL are likely to be among the population with a greater susceptibility to NIHL, simply because of their existing NIHL. Additionally, as the susceptibility to NIHL likely has genetic components, patients with a family history of NIHL may have a higher likelihood of having NIHL from VEMP stimuli (Konings et al, 2009). Susceptibility to NIHL is not limited to history of hearing loss. Patients who are or were recently undergoing treatments including potentially ototoxic medications may be at higher risk for NIHL from VEMP stimuli (Boettcher et al, 1987). These may include patients on platinum-based chemotherapy (e.g., cisplatinum, carboplatinum) and patients on aminoglycoside antibiotics. A comprehensive case history is advised to determine if patients are on potentially ototoxic medications, have a history of NIHL, or who have a family history of NIHL. Care should be taken with any patient who has a potentially increased susceptibility to NIHL to ensure low exposures from VEMP testing.

WHAT STIMULUS PARAMETERS SHOULD BE CONSIDERED FOR SAFE VEMP TESTING?

Development of an appropriate clinical protocol for safe and effective VEMP testing requires emphasis on several stimulus parameters. Table 6 provides a protocol that generally does not exceed NIOSH-recommended noise exposure values. Variation in any of these parameters will affect the overall output level. For example, if the number of sweeps or intensity is changed, the output level and total exposure time will vary accordingly. Calculating exposure levels for clinical protocols is important and should be combined with patient variables such as ear canal volume or susceptibility to noise exposure. The clinician should be mindful not only of output level for each variation in protocol but also of the projected dose for all testing to be completed. VEMP testing requires high-intensity stimulation, and the clinician will note an expected decreased amplitude with reduction in the intensity level (Colebatch et al, 1994). Further, alterations in the stimulus duration will affect amplitude and latency (Welgampola and Colebatch 2001); however, reducing the stimulus duration may not lead to clinically significant changes in the response. Importantly, changing these components could significantly reduce the noise exposure with minimal change to the response.

A Tool for Calculating Noise Exposure from VEMP Stimuli

Included in the supplementary material for this article is a Microsoft Excel (2013) worksheet that can

Table 6. Example of Stimulus Parameters for 500-Hz Tone-Burst Air-Conducted Stimuli That Do Not Generally Exceed Recommended Noise Exposure Levels

Stimulus Parameter	Value
Intensity	≤126 dB pSPL*
Stimulus duration	4 msec (e.g., 2 msec rise/fall, 0-msec plateau)
Gating	Blackman
Number of sweeps	
cVEMP	<100
oVEMP	<150
Number of repetitions	Two trials at high-intensity level Two trials at low-intensity level Consider threshold search in 10-dB steps if asymmetry or concern for third-window disorder

Note: *Include corrections for ear canal volume if necessary.

calculate the noise exposure level, taking into account stimulus intensity, duration, number of sweeps per trial, and number of trials. The worksheet provides three metrics that can weigh the potential risk to an individual patient from their VEMP exposure: the NIOSH and EU DRCs, and a total energy over 1sec exposure as described by Colebatch and Rosengren (2014). A clinician can use these metrics to judge whether the patient may be at increased risk for NIHL due to VEMP stimulus exposure. Importantly, this tool allows clinicians to calculate VEMP exposure from tone-burst stimuli, but cannot be used for click stimuli.

Using this new exposure calculation tool, the exposure in past VEMP studies can be calculated. As an example, Stromberg and colleagues (2016) identified significant changes in cochlear function following exposure to a specific VEMP protocol. In that study, the researchers exposed participants to 192 impulses of a 6-msec 500-Hz tone burst at 130 dB peSPL. This equals a $L_{aeq,8hr}$ of 86.18 dB, representing the average A-weighted level of sound exposure over an 8-hr period. Using the calculator provided by the current authors, this exposure equals a NIOSH DRC noise dose of 131.1% and a total energy of 130.6 dB over 1 sec. As the noise dose in that study exceeded 100%, it is unsurprising that those research participants experienced cochlear changes in the form of reduced DPOAEs. Indeed, this outcome supports the authors' conclusions that extended stimuli intensity or repetition during VEMP testing should be avoided to reduce the risk of noise-induced cochlear injury.

CONCLUSIONS AND FUTURE DIRECTIONS

VEMP testing can be a safe and effective tool in the vestibular test battery. Clinicians must consider the general impact of NIHL from VEMP stimuli exposure and should monitor each patient's noise exposure from the VEMP test, as well as total daily exposure. Clinicians should also be mindful of certain populations who could be at specific risk for NIHL from VEMP exposure, including children and patients with a history of NIHL. Caution should be taken when measuring VEMPs in patients with certain other disorders, including tinnitus, hyperacusis, and third-window phenomena such as enlarged vestibular aqueduct syndrome or SSCD. By following the suggestions listed above, clinicians can reduce the risk of inducing hearing loss in their patients.

This article provides a sample protocol that, if followed, may reduce the patient's susceptibility for hearing loss from VEMP exposure while providing adequate diagnostic information. While this protocol may not be ideal for every clinic, it provides a framework for establishing a VEMP test battery that limits noise exposure to the auditory system. Using this or a similar protocol can help to also provide a consistent test, which can be easily repeated across clinics. Clinicians and researchers should always report VEMP testing results, including threshold levels, in dB p/peSPL, to allow for easy interpretation by other clinicians and researchers. If clinicians are unaware of what their p/pe SPL output is, it is often helpful to work with the individual(s) calibrating the equipment to obtain these values.

While this article reviews the safety of tone-burst VEMP protocols to the auditory system, additional VEMP protocols are not discussed. This protocol does not apply to click-evoked VEMPs. The supplemental calculation spreadsheet cannot be used to estimate noise exposure for hearing loss from click stimuli. Further research is necessary to understand auditory impact from bone-conducted stimuli. As these technologies mature in the research laboratory and move into clinical practice, clinicians and researchers should establish guidelines for clinical use of these and other novel stimuli that are safe for the auditory system.

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