DEVELOPING AN IDEAL CLINICAL PROTOCOL FOR RECORDING CERVICAL VESTIBULAR EVOKED MYOGENIC POTENTIALS

by

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As members of the Audiology Doctoral Project Committee, we certify that we have read the Audiology Doctoral Project prepared by Athena Luong, titled Developing an Ideal Clinical Protocol for Recording Cervical Vestibular Evoked Myogenic Potentials and recommend that it be accepted as fulfilling the Audiology Doctoral Project requirement for the Degree of Doctor of Audiology.

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Final approval and acceptance of this Audiology Doctoral Project is contingent upon the candidate's submission of the final copies of the Audiology Doctoral Project to the Graduate College.

I hereby certify that I have read this Audiology Doctoral Project prepared under my direction and recommend that it be accepted as fulfilling the Audiology Doctoral Project requirement.

Date: 4/13/2020

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Abstract

A cervical vestibular evoked myogenic potential (cVEMP) is a relatively new specialized test that has become an important component in a comprehensive vestibular test battery. cVEMPs examine the integrity of the saccule, an otolithic organ within the vestibule of the inner ear, and the inferior portion of the vestibular nerve. Based on review of the literature, there is great variability in the way this test is executed in terms of electrode placement and stimuli selection across individual clinics, which can result in varying results. In an attempt to determine an ideal clinical protocol that will ideally allow comparative results across all clinics, this study simultaneously recorded cVEMPs from three different electrode placements on the sternocleidomastoid muscle and varied the acoustic stimuli conditions. Results indicated that a 500 Hz tone burst, regardless of the duration, resulted in the most robust cVEMP response across all subjects for all locations. Additionally, the top electrode location on the SCM resulted in the most robust cVEMP response across all subjects and under all conditions.

Key words: cervical vestibular evoked myogenic potentials, protocol, conditions.

Introduction

History

Petro Tullio (1929) was the first to explore vestibular system sensitivity to auditory stimuli. Through research with pigeons, Tullio was able to demonstrate that the vestibular system could be stimulated by sound (McCaslin & Jacobson, 2016). In 1960, Von Bekesy discovered that a tap to the head created a vibration to travel throughout the head leading to linear accelerations at the level of the mastoids, which result in the activation of vestibular afferent neurons (Halmagyi, McGarvie, & Curthoys, 2008). However, it was Bickford, Jacobson, and Cody (1964) that were the first to describe responses that could activate vestibular neurons which resulted in the suppression of the sternocleidomastoid muscle (SCM), which were later categorized as vestibular evoked myogenic potentials (VEMPs) in 1992 by Colebatch and Halmagyi. Subsequently, Colebatch and Halmagyi (1992) demonstrated that these potentials were a true response originating from the vestibular system when they found that the responses diminished after vestibular nerve section. A few years later in 1995, Colebatch and Halmagyi were the first to publish that VEMPs could be recorded reliably from the sternocleidomastoid muscle (SCM) and coined the term cervical vestibular evoked myogenic potential (cVEMP).

Anatomy

The human vestibular labyrinth is located within the petrous portion of the temporal bone. Within the vestibular labyrinth lies the vestibular end-organs, that comprise the three semicircular canals (horizontal, anterior vertical, and posterior vertical) and the two otolith organs (saccule and utricle). These vestibular end-organs are responsible for coding the orientation of the head to gravity as well as rotational and linear movement (Murofushi & Kaga, 2009). The primary generator of the cVEMP is the saccule, one of two sensory otolithic organs in the vestibular system, whose afferents project to vestibular nuclei via the inferior portion of the vestibular nerve. The saccule's primary role is to sense linear acceleration or gravity with respect to a sagittal plane (Blakey & Wong, 2015). The vestibular portion of the eighth cranial nerve (CN VIII) bifurcates into the superior and inferior branches. When a high intensity stimulus is presented to the ear via air conduction, it stimulates the ipsilateral saccule due to its close proximity to the stapes footplate, which then activates the afferents of the inferior branch of the vestibular nerve, which projects to the medial and inferior vestibular nuclei. From the vestibular nuclei, efferent fibers project through the lateral vestibulospinal tract to the SCM, producing a muscle reflex (Ferber-Viart, Dubreuil, & Duclaux, 1999). In simpler terms, a cVEMP is an ipsilateral, inhibitory muscle reflex following the presentation of a high level acoustic stimuli that activates the saccular afferent pathway (Rosengren, Welgampola, & Colebatch, 2010).

Comprehensive Vestibular Test Battery

cVEMPs are now commonly utilized as a diagnostic tool and is a valuable component in a complete vestibular test battery as it is the only test that can assess the integrity of the saccule and inferior branch of the vestibular nerve. Other tests within this test battery, such as videonystagmography (VNG) and caloric tests are limited to assessment of function of the horizonal semicircular canals. To obtain a cVEMP, tonic contraction of the sternocleidomastoid muscle (SCM) is required. When the SCM is at rest, a cVEMP cannot be recorded (Rosengren, Welgampola, & Colebatch, 2009). Historically, cVEMPs have been recorded from various muscles, such as the trapezius, triceps, and gastrocnemius muscles (Jacobson et al., 2011).

Additionally, the splenius capitis muscle has also been reported as a reliable muscle for recording cVEMPs (Camp, Gu, Cushing, Gordon, & Corneil, 2017). However, in the vast majority of audiological settings, cVEMPs are recorded from the sternocleidomastoid muscle due to its direct connection with the vestibulospinal tract (Jacobson et al., 2011). It is important to note that cVEMPs can be recorded in those with a sensorineural hearing loss. As long as the stimuli can travel through the external auditory canal and the middle ear can conduct the stimuli to the inner ear to stimulate the saccule, a response can be obtained. Therefore, individuals with a conductive hearing loss or mixed hearing loss will have absent responses.

cVEMPs are characterized by a short-latency, biphasic waveform that begins with a positive peak followed by a negative peak. The first positive deflection is commonly known as "p13" as it typically occurs around 13 milliseconds (ms). The second deflection is labeled "n23", as it is a negative peak occurring around 23 ms (McCaslin & Jacobson, 2016). These latency measures were first described by Colebatch et al. (1994) and the peak deflections are dependent on the polarity of the montage. The peak polarity can be inverted with a negative deflection followed by a positive deflection depending on the recording location of the electrode on the SCM (Ashford et al., 2016). See Figure 1 and Figure 2. cVEMP absolute latencies for p13 and n23 can also vary across individuals. Colebatch et al. (1994) found a mean latency of 16.1 +/- 2.1 ms for p13, whereas Blakley & Wong (2015) found a broader range of 13.9 to 19.2 ms for p13 latencies. For n23, Colebatch et al. (1994) noted a mean latency of 23.8 +/- 2.2 ms and Blakley & Wong (2015) reported 22.9 to 30.3 ms.

Figure 1. A biphasic cVEMP waveform in response to a 750 Hz air-conducted tone burst showing a positive deflection (p13) and negative deflection (n23). The inverting electrode was placed near the sternum.

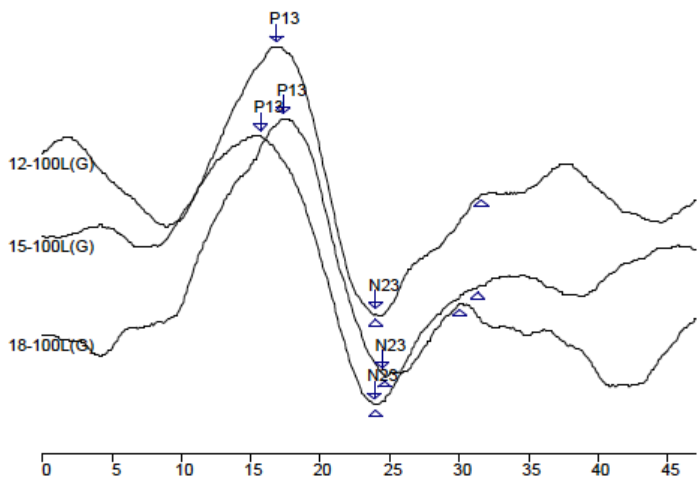
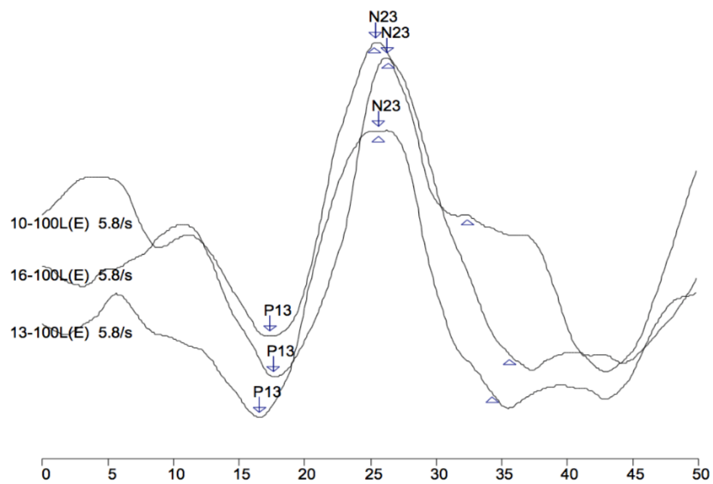


Figure 2. A biphasic cVEMP waveform in response to a 750 Hz air-conducted tone burst showing a negative deflection followed by a positive deflection. The inverting electrode was placed on the upper third of the SCM towards the level of insertion at the mastoid.



Thresholds are also an important measure of cVEMP responses. A cVEMP threshold is the lowest intensity at which a cVEMP can be measured and reproduced (McCaslin & Jacobson, 2016). cVEMPs are large responses and will dissipate if presented below an individual's threshold. cVEMP thresholds are commonly within the range of 70 – 95 dB nHL (Colebatch et al., 1994). However, individuals with certain types of vestibular pathologies may have thresholds that are significantly lower as noted below.

Due to its high sensitivity and specificity (80-100%), cVEMPs are utilized to assist with diagnosing superior semicircular canal dehiscence (SSCD), which is a bony defect in the superior semicircular canal (Diaz, Lesser, & Alarcon, 2017) that results in lowered impedance of energy flow into the affected semicircular canal by shifting away fluid motion away from the cochlea. Consequently, this disruption changes the normal physiological function of the labyrinth (Hunter et al., 2016). This bony defect is also known as the “third window” because it creates hyper bone-conduction thresholds and can result in a false air-bone gap on audiograms. SSCD can be congenital or acquired, such as from a head injury. Individuals with SSCD can present with a myriad of auditory symptoms, which include: autophony, pulsatile tinnitus, hyperacusis, hearing loss, etc. (Diaz et al., 2017). Additionally, they may also experience vestibular symptoms, specifically when induced by loud noises (Tullio’s phenomenon), straining, or when there are changes in pressure in the external auditory canal (Diaz et al., 2017). When suspected of SSCD, a cVEMP response reveals lower thresholds in the affected ear.

cVEMP Recording Parameters

There are a variety of factors that must be taken into account when recording a cVEMP, which include: stimulus intensity, frequency and duration, filtering of the response, location of electrode placement, and tonic contraction of the SCM. Many studies have been performed that investigated cVEMP recording parameters.

Colebatch et al. (1994) found that the response amplitude was significantly larger when the stimulus intensity was higher. For example, they found that a response to a 100 dB nHL click was 36% larger than a response at 95 dB nHL (Colebatch et al., 2004). Lee Lim, Clouston, Sheean, and Yiannnikas (1995) had similar findings with a 100 dB nHL stimulus was 30% larger than 95 dB nHL.

Table 1. Stimulus intensity across various studies.

Study	**Stimulus Intensity**
Cheng (2003)	95 dB nHL
Kelsch et al. (2010)	90 dB nHL
Wang et al. (2004)	105 dB nHL
Welgapola & Colebatch (2001)	105 dB nHL

cVEMP responses can also be recorded with various stimulus frequencies, including: 500, 750, 1000, or even 2000 Hz. Todd, Cody, and Banks (2000) found that maximum cVEMP amplitudes were obtained when the stimulus frequency was between 300 and 650 Hz, whereas Welgampola & Colebatch (2001) found a broader range of up to 1000 Hz that demonstrated the most robust response. Further, Isaacson, Murphy, and Cohen (2006) utilized a 750 Hz tone burst in their study, whereas Dennis et al. (2014) used a 500 Hz tone burst. Singh, Kumar, and Barman (2014) found that a duration of 2 cycles rise/fall and 1 cycle plateau produced the most robust and consistent response. However, Dennis et al. (2014) utilized a 500 Hz tone burst with a 0 cycle rise/fall and 2 cycle plateau.

Table 2. Stimulus frequency and duration across various studies.

Study	Stimulus Frequency and Duration (if noted)
Cheng et al. (2003)	500 Hz TB (1 cycle rise/fall, 2 cycles plateau)
Dennis et al. (2014)	500 Hz TB (0 cycle rise/fall, 2 cycles plateau)
Isaacson et al. (2006)	750 Hz TB (2 cycles rise/fall, 1 cycle plateau)
Todd et al. (2000)	300 – 650 Hz TB
Welgampola & Colebatch (2001)	300 – 1000 Hz TB

In addition, filter settings for recording cVEMPs have also varied across the literature. Akin & Murnane (2008) found that dominant energy from an electromyography (EMG) signal can be found between 40 – 150 Hz. Thus, they concluded that filter settings for recording cVEMPs should have a low pass between 1000 – 2000 Hz and a high pass between 5 – 20 Hz. Other studies have utilized different filter settings as shown in Table 3.

Table 3. Filter settings across various studies.

Study	Filter Settings
Akin & Murnane (2008)	5 – 2000 Hz
Colebatch et al. (1994)	8 – 1600 Hz
Rosengren (2015)	5 – 2000 Hz
Sheykholeslami et al. (2001)	20 – 2000 Hz

The electrode montage used for recording cVEMPs are also varied across studies. Placement of electrodes on the SCM are critical for obtaining a robust response. Sheykholeslami, Murofushi, and Kaga (2001) specifically examined the placement of SCM electrode in recording cVEMP for clinical use. They used the same acoustic stimuli for all positions (upper portion of the SCM at the level of the mandibular angle, the middle portion of the SCM, and immediately above sternal and clavicular origins of the SCM). Findings from this study indicated that the upper portion of the SCM provided the most robust responses. However, the middle portion of the muscle provided the most consistent responses (Sheykholeslami, Murofushi, & Kaga, 2001).

Table 4. Electrode placement across various studies.

Study	**Placement**
Meyer et al. (2014)	Upper half and middle third of SCM
Piker et al. (2013)	Midway of SCM
Rosengren (2015)	“Belly” of SCM

Lastly, there are also several ways to activate the SCM. Isaacson et al. (2006) evaluated whether the position of activation of the SCM would have an effect on cVEMPs. They obtained cVEMPs by using the following methods for activation of the SCM: sitting upright with head turned to one side using hand to press against head for resistance, supine with head lifted straight up, and supine with head lifted up and turned away from recording SCM. Isaacson et al. (2006) found that subjects who were in the supine position with their head lifted up and turned away from the SCM resulted in the greatest cVEMP amplitudes. However, Dennis et al. (2014) noted specifically in their study that the head should be lifted and then turned 30 degrees contralaterally. In contrast, Camp et al. (2017) recorded a cVEMPs from an entirely different muscle – splenius capitis muscle (SPL), a dorsal neck muscle. They compared cVEMPS that were obtained from activating the SPL and SCM and found that activation of the SPL was just as reliable as responses from activation of the SCM.

cVEMP Response Indices

The following parameters are commonly evaluated: threshold, amplitude, and latency of p13 and n23. Less commonly, interaural differences may be evaluated as well, such as: interaural symmetry ratio, interaural latency differences, and interaural amplitude differences. cVEMP thresholds are categorized as the lowest intensity at which a cVEMP can be obtained and reproduced (Jacobson et al., 2011). Thresholds can be obtained by using a method similar to the Hughson-Westlake for pure-tone audiometry, by increasing or decreasing the intensity level in 5 dB increments (Blakley & Wong, 2015). Normative data regarding threshold levels for normal hearing individuals without vestibular pathologies vary across for the literature. For instance, Colebatch et al. (1994) have suggested that cVEMP thresholds can fall between 75-80 dB nHL using a click stimulus; whereas, Blakley & Wong (2015) reported a broader range of 70-95 dB nHL using a 500 Hz tone burst. Additionally, age effects play a role in the variability of threshold levels as it has been recorded that an increase in age will also result in an increase in cVEMP threshold (Piker et al., 2013).

Normative data regarding cVEMP amplitude measures are also highly variable and are dependent on characteristics of the stimuli and level of muscle contraction (level of electromyogram). Cheng, Huang, & Young (2003) evaluated the influence of 95 dB nHL clicks versus 95 dB nHL short tone-bursts on VEMPs and found a significant difference in amplitude. Click evoked cVEMPs had an amplitude range of 119.55 +/- 44.03 μV versus a 500 Hz tone-burst evoked cVEMPs, which were 102.84 +/- 44.56 μV (Cheng, Huang, & Young, 2003). Akin et al. (2004) found that maintaining an electromyogram (EMG) level of 30 to 50 μV of the muscle is optimal for recording cVEMPs. They reported that the relative EMG level is highly correlated with cVEMP amplitudes despite the type of stimulus used, such as a click versus tone-burst (Akin et al., 2004). Further, Lim et al. (1995) have also reported that VEMP amplitudes are highly dependent on stimulus characteristics and EMG level of the muscle.

A cVEMP is the only test that can assess the integrity of the saccule and inferior branch of the vestibular nerve and diagnose SSCD. Despite the importance of this test, it is evident from a review of the literature that there is great variation in the manner in which cVEMP responses are obtained across different clinical settings based on review of the literature. Thus, the goal of this study is to develop a clinical protocol for recording cVEMPs that can be used across clinics to provide a consistent method of obtaining cVEMPs for comparative measures.

As a result, we have selected the following protocol for our study. We have chosen to place electrodes specifically on three locations on the SCM for recording cVEMPs as noted below in the methods. Our method of activation is to have the participants lay supine with their heads turned 90 degrees contralaterally from the tested ear and lifted. This places the SCM in a maximally contracted position when the head is lifted vertically. We have chosen to use 500 and 750 tone bursts with a duration of 4 (2 cycles plateau, 1 cycle rise/fall) and 5 cycles (1 cycle plateau, 2 cycles rise/fall) each with a total of 4 stimuli that will be presented at 100 dB nHL. Lastly, the filter settings will be 10 – 300 Hz as we are not interested in any responses earlier than 3 ms or later than 100 ms.

Methodology

Participants

Twelve healthy individuals (9 women and 3 men) between the ages of 23-42 years old participated this study. Their average age was 28.6 years. Participation in the study was voluntary and informed consent was obtained from all individuals in compliance with the University of Arizona's policy on the International Review Board (IRB) to protect human subjects.

All subjects' ears were examined via otoscopy and tympanometry. Exclusion criteria for all participants included current complaints of dizziness or imbalance, neck mobility difficulty, cerumen impaction, and an abnormal tympanogram indicating abnormal middle ear status. Participants were excluded if their tympanograms were not defined as a Jerger Type A tympanogram with a middle ear pressure range from -50 to + 50 mmH_2O.

Equipment and Stimuli

The Intelligent Hearing Systems (IHS) SmartEP® 8-channel auditory evoked potential system was used for all measures. This system allowed us to record from the 3 different electrode positions simultaneously so that all measures were recorded under the exact same conditions, allowing a direct comparison of effects of electrode position and stimulus characteristics on the cVEMP response.

The following stimuli were used and presented ipsilaterally in an alternating phase via air-conduction to each subject's ear through ER-3A insert earphones: 500 Hz (1 cycle plateau, 2 cycles rise/fall), 500 Hz (2 cycles plateau, 1 cycle rise/fall), 750 Hz (1 cycle plateau, 2 cycles rise/fall), and 750 Hz (2 cycles plateau, 1 cycle rise/fall). Each stimulus was presented at a rate of 5.8 Hz. For the purpose of this study, each varying stimuli will be indicated as a type of condition.

cVEMP Protocol

Once the subjects passed an otoscopic and tympanometric screening, their skin was prepped with an alcohol wipe and NuPrep gel in the following areas: midline forehead, chin, and both sternocleidomastoid muscles. Following skin preparation, Ambu Neuroline surface electrodes were placed on the forehead and chin as the ground and non-inverting, respectively. A measurement of each SCM was obtained from insertion of the muscle at the level of the mastoid to the sternum. A midline point was marked, as well as 1 inch below (bottom) and 1 inch above (top). Electrodes were placed on these three exact areas medially on each muscle. See Figure 3. Impedances of all electrodes were checked prior to cVEMP acquisition.

Figure 3. Demonstration of objective measurement, as well as electrode positioning and placement on the sternocleidomastoid muscle.

All participants reclined on a comfortable examination chair that was adjusted such that the subjects were in the supine position. They were instructed to turn their head as far away from the test ear as possible and to lift their head as high as possible with the introduction of the acoustic stimulus. Upon cessation of the stimulus, they were instructed to return to a neutral neck position facing upward. Participants were given a break between each stimulus change.

Results

Table 5 is a case processing summary which indicates the number of cVEMP responses that were deemed acceptable and included for analysis per subject, ear, condition, and location. Table 5 demonstrates that cVEMP responses were successfully recorded from 12 subjects and 72 waveforms were obtained for each subject for a total of 864 cVEMP responses. Sixty-two responses were discarded and excluded from the analysis. In these cases, we were unable to use the data due to high variability resulting in unidentifiable p13 and n23 peaks for our measurements. Thus, a total of 802 waveforms were included in the analysis. The peak-to-peak (PP) values and absolute latencies for all included responses were extracted from the recorded waveforms and all peaks were marked and confirmed by two observers (AL & DV). A mixed model analysis of the dependent variable, cVEMP PP value, was performed for location and condition (stimuli). For each subject, there was repeatability and intra-subject consistency. Covariance parameters of inter-subject variability indicated a significant level of approximately 25% variance across subjects. In other words, intra-subject cVEMP responses in terms of PP value were consistent, whereas inter-subject cVEMP responses are more variable.

Table 5. A case processing summary of all cVEMP responses that were acquired and excluded across subjects, ear, condition, and location of electrode placement.

Subject	# of cVEMP responses
1	70
2	72
3	65
4	62
5	72
6	72
7	72
8	60
9	59
10	71
11	69
12	59
Ear	
Left	393
Right	409
Condition	
500 Hz 1-2-1	201
500 Hz 2-1-2	206
750 Hz 1-2-1	196
750 Hz 2-1-2	199
Location	
Top	282
Middle	260
Bottom	260
Valid	802
Excluded	62
Total	864

Condition

A one-way ANOVA with pairwise comparison and a 95% confidence interval for difference with a significance level of $p < 0.0167$ was used for comparisons of the three conditions across all locations on the SCM. A Bonferroni correction was applied to the significance level to account for alpha slippage. The results demonstrate that the envelope of the stimuli, whether it was 2 cycles rise/fall and 1 cycle/plateau (2-1-2) or 1 cycle rise/fall and 2 cycles plateau (1-2-1), did not have a significant effect on the PP value of cVEMP responses for this population. Table 6 demonstrates that a 500 Hz tone burst has an overall significant effect on PP value in comparison to a 750 Hz tone-burst with a mean difference in PP value ranging from 34.877 – 56.838 μV. Table 7 demonstrates the grand average means for each condition across all subjects, ears, and locations of electrodes on the SCM. As noted, the 500 Hz tone burst, regardless of the envelope, resulted in the greatest mean PP value.

Table 6. A fixed effect model was used for pairwise comparisons of each condition across all subjects. Areas that are shaded and bolded represent the greatest mean difference of PP value for the corresponding condition.

Pairwise Comparison - Condition		95% Confidence Interval for Difference		Std. Error	Significance Level $p < 0.0167$
Condition	Mean Difference of PP Value (μV)	Lower Bound	Upper Bound		
500 Hz 1-2-1					
500 Hz 2-1-2	0.787	-18.403	19.977	9.776	0.936
750 Hz 1-2-1	**34.877**	15.417	54.338	9.913	0.000
750 Hz 2-1-2	**56.838**			9.868	0.000
500 Hz 2-1-2					
500 Hz 1-2-1	-0.787	-19.977	18.403	9.776	0.936
750 Hz 1-2-1	**34.090**	14.758	53.422	9.848	0.001
750 Hz 2-1-2	**56.051**	36.792	75.309	9.811	0.000
750 Hz 1-2-1					
500 Hz 1-2-1	-34.877	-54.338	-15.417	9.913	0.000
500 Hz 2-1-2	-34.090	-54.422	-14.758	9.848	0.001
750 Hz 2-1-2	**21.961**	2.439	41.482	9.944	0.028
750 Hz 2-1-2					
500 Hz 1-2-1	-56.838	-76.209	-37.467	9.868	0.000
500 Hz 2-1-2	-56.051	-75.309	-36.792	9.811	0.000
750 Hz 1-2-1	-21.961	-41.482	-2.439	9.944	0.028

Table 7. Grand average means for each condition across all subjects, ears, and locations of electrode on SCM.

Conditions	Mean PP value (μV)	Std. Error
500 Hz 1-2-1	247.309	18.077
500 Hz 2-1-2	246.521	18.042
750 Hz 1-2-1	212.431	18.120
750 Hz 2-1-2	190.471	18.091

Location

A one-way ANOVA with pairwise comparison and a 95% confidence interval for difference with a significance level of $p < 0.025$ was used for the two comparisons between the top, middle, and bottom electrode placement on the SCM for all conditions. A Bonferroni correction was applied to the significance level to account for alpha slippage. The results in Table 8 demonstrate that the top electrode placement, one inch medially above midpoint of the SCM, has a significant effect on PP values of the cVEMP responses for this population. Table 9 shows the grand average means for each electrode location across all subjects, ears, and conditions. This reveals that the top, bottom, and middle resulted in the highest to lowest mean PP value, respectively.

Table 8. A fixed effect model was used for pairwise comparisons of each location across all subjects. Areas that are shaded and bolded represent the greatest mean difference of PP value for the corresponding location. Areas that are shaded and bolded represent the greatest mean difference of PP value for the corresponding location.

Pairwise Comparison - Location		95% Confidence Interval for Difference		Std. Error	Significance Level $p < 0.025$
Location	Mean Difference of PP Value (μV)	Lower Bound	Upper Bound		
Top					
Middle	**130.989**	110.237	76.882	8.474	0.000
Bottom	**93.560**	114.335	147.644	8.496	0.000
Middle					
Top	-130.989	-147.644	-114.335	8.484	0.000
Bottom	-37.430	-54.490	-20.369	8.691	0.000
Bottom					
Top	-93.560	-110.237	-76.882	8.496	0.000
Middle	37.430	54.490	20.369	8.691	0.000

Table 9. Grand average means for each electrode location across all subjects, ears, and conditions.

Location of Electrode on SCM	Mean PP value (μV)	Std. Error
Top	299.033	17.682
Middle	168.043	17.775
Bottom	205.473	17.781

Location and Condition

A one-way ANOVA with pairwise comparison and a 95% confidence interval for difference with a significance level of $p < 0.0.0083$ was used for the six comparisons between the three electrode locations and four conditions. A Bonferroni correction was applied to the significance level to account for alpha slippage. The results indicate that location and condition do not interact and do not have any influence on one another for this population. However, we can infer from the significance of the location on PP value and the significance of the condition on PP value that the top location with a 500 Hz tone-burst will have a high likelihood of resulting in a robust cVEMP response. See Table 10.

Table 10. A fixed effect model and pairwise comparison of both condition and location on PP value. Areas that are shaded and bolded represent the greatest mean difference of PP value for the corresponding location.

Condition	Location of Electrode on SCM	Mean PP value (μV)	Std. Error
500 Hz 1-2-1	**Top**	**328.784**	20.311
	Middle	188.728	20.798
	Bottom	299.415	20.654
500 Hz 2-1-2	**Top**	**331.958**	20.311
	Middle	177.012	20.408
	Bottom	230.594	20.755
750 Hz 1-2-1	**Top**	**280.502**	20.515
	Middle	169.265	20.680
	Bottom	187.527	20.880
750 Hz 2-12	**Top**	**254.887**	20.411
	Middle	142.168	20.874
	Bottom	174.358	20.572

Latency

A mixed model analysis with random and fixed effects were also perfomed for latency and found that there was high variability between subjects for P13 and N23 latencies, however, this is within the norm (Blakley & Wong, 2015). Within subject variablity was low and intra-subject latencies were consistent for every subject.

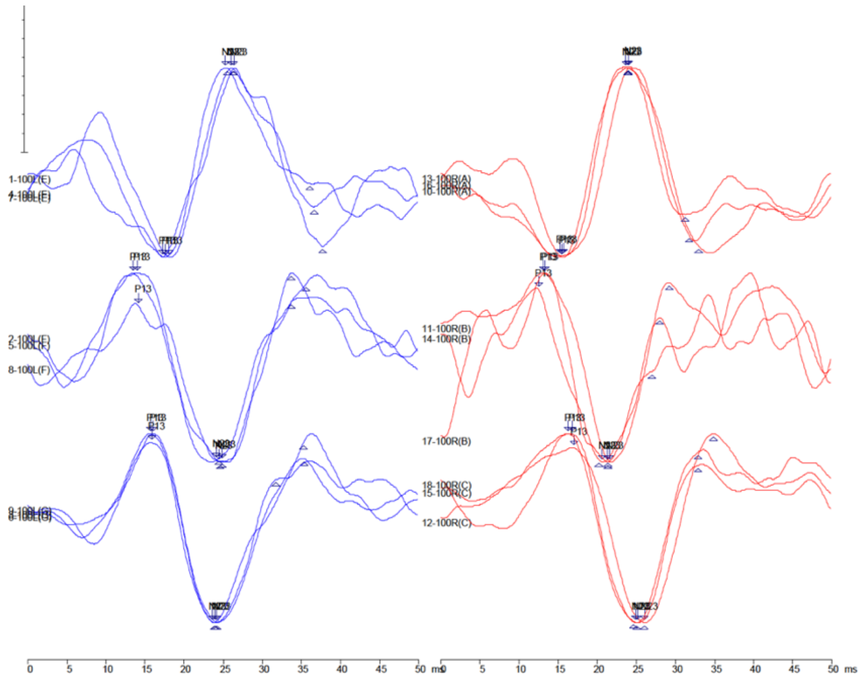
Interaural differences

Interaural differences was not a key aspect of this study. During the process of filtering out cVEMP responses that were included and excluded in the study, 39 of the 62 waveforms that were discarded were from the left ear across all subjects which could have skewed our data if we were evaluating interaural differences.

Polarity Reversal

An interesting finding from this study was peak polarity reversals (see Figure 4) within 22 ears from our 12 subjects (total of 24 ears). Out of 24 ears, six ears had cVEMP responses with a polarity reversal for the middle and bottom location under all conditions. Sixteen ears had cVEMP responses with a polarity reversal for the bottom location only. Lastly, two ears had cVEMP responses that did not have any occurrence of polarity reversal.

Figure 4. A peak polarity reversal seen in Subject 10 for both ears at the middle and bottom electrode locations.



Discussion and Conclusion

Findings from this study demonstrated that for this population, the top electrode location on the SCM resulted in the most robust cVEMP response across all subjects and under all conditions. When the top electrode location was compared to the middle electrode location, the top electrode location was 130.989 μV larger in mean difference of PP value. When the top electrode location was compared to the bottom location, the top electrode location was 93.560 μV larger in mean difference of PP value. Additionally, the top electrode location provided the most consistent cVEMP responses with reliable p13 and n23 peaks across all subjects, under all conditions, with the middle and bottom electrode locations resulting in variable waveforms and peaks.

Findings from this study also revealed that for this population, a 500 Hz tone burst, regardless of the duration, resulted in the most robust cVEMP response across all subjects for all locations when compared to a 750 Hz tone burst. There was no significant effect between the 500 Hz tone burst with a 4 cycle duration (1 cycle rise/fall and 2 cycle plateau) and a 500 Hz tone burst with a 5 cycle duration (2 cycles rise/fall and 1 cycle plateau). Though there was not a significant effect between the two 500 Hz tone bursts, when compared to a 750 Hz tone burst (both durations), the 500 Hz tone burst resulted in a cVEMP response of greater amplitude, with a mean difference of PP value ranging from 34.877 to 56.838 μV.

In regards to the variability of cVEMP responses, we suspect that this may be due to the surrounding neck muscles that can be contributing to the response and the possibility of the reference electrode response contributing to the inconsistent responses as well. First, there are several groups of muscles within the neck that may play a significant role in contaminating cVEMP responses from the SCM, resulting in inconsistent waveforms. For instance, the platysma muscle is a broad sheet of muscle that almost entirely covers the SCM and runs transversely over it (Gilroy et al., 2009). The omohyoid muscle group comprise superior and inferior bellies that are situated beneath the SCM (Gilroy et al., 2009). The inferior belly of the omohyoid runs medially and parallel to the SCM and the superior belly runs transversely underneath the SCM muscle and attaches to the hyoid bone (Gilroy et al., 2009). Additionally, there is another group of paired muscles that are located in the lateral aspect of the neck called the scalene muscles (Gilroy et al., 2009). These large muscles are situated dorsally to the SCM (Gilroy et al., 2009). Due to the number of muscles surrounding the SCM, it is possible that the crossing of multiple muscle fibers result in a variable cVEMP response.

In regards to the occurrence of unidentifiable peaks, high variability of cVEMP waveforms, and polarity reversals, there are a few things to contemplate. First, differential amplification recording was used for this study with a ground, inverting, and non-inverting electrode. This may not have been necessary in the acquisition of cVEMPs as differential amplification recording is typically used for auditory brainstem responses, which are incredibly small (0.1 to 1 μV); whereas, cVEMP responses are much larger in comparison (> 150 μV). Differential amplification recording may result in losing parts of the cVEMP response itself as much of the muscle potential may also be "seen" by the reference electrode, resulting in some of the SCM response in the reference electrode reducing some of the desired response in the recording site on the SCM via differential amplification (common mode rejection). Second, the geometry of the fiber tract of the SCM may play a role in the variable responses obtained in this study, specifically for the middle location. If the orientation of neurons were structured as open-field, this would result in an additive electrical field which would generate a large evoked potential. However, Ashford et al. (2016) noted in their study that the polarity reversal may be due to the theory of SCM compartmentalization in that the bottom location, near the sternum, as separate innervation zones (Ashford et al., 2016).

Based on the results from this study, it is recommended that clinicians performing cVEMPs use our protocol and objective method of measuring the SCM length and placing the inverting electrode in the center of the muscle and exactly 1 inch above the midpoint of the SCM. This is a more consistent technique of placing the electrode on the portion of the SCM that results in the most robust cVEMP. This will also allow clinicians from different clinics to replicate the exact location with simply a tape measure. Additionally, based on our study, a 500 Hz tone-burst is recommended rather than a 750 Hz tone-burst.

Limitations

A general limitation of this present study was the sample size and lack of EMG monitoring of the SCM contraction as tonic contraction of the muscle is critical for obtaining a robust cVEMP response. Additionally, the study included 12 relatively young students from the University of Arizona with more female participants than male participants. In future studies, it would be beneficial to recruit more adults to determine if this protocol would provide the same results. It would also be advantageous to perform a more comprehensive screening, including audiometric testing to rule out minimal conductive hearing loss that may be undetected via tympanometry.

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