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Correlation of Superior Canal Dehiscence Surface Area with Vestibular Evoked Myogenic Potentials, Audiometric Thresholds, and Dizziness Handicap

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Abstract

Objective—To correlate objective measures of vestibular and audiometric function as well as subjective measures of dizziness handicap with the surface area of the superior canal dehiscence (SCD)

Study Design—Retrospective chart review and radiological analysis

Setting—Single tertiary academic referral center

Patients—Preoperative CT imaging, patient survey, audiometric thresholds, and VEMP testing in patients with confirmed SCD

Intervention(s)—Image analysis techniques were developed to measure the surface area of each SCD in CT imaging.

Main outcome measure(s)—Preoperative ocular and cervical VEMPs, air and bone conduction thresholds, ABG, dizziness handicap inventory scores, and surface area of the SCD

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Results—Fifty-three patients (mean age 52.7 years) with 84 SCD were analyzed. The median surface area of dehiscence was 1.44 mm² (0.068-8.23 mm²). Ocular VEMP amplitudes ($r = 0.61$, $p < 0.0001$), cervical VEMP amplitudes ($r = 0.62$, $p < 0.0001$), air conduction thresholds at 250 Hz ($r = 0.25$, $p = 0.043$), and ABG at 500 Hz ($r = 0.27$, $p = 0.01$) positively correlated with increasing size of dehiscence. An inverse relationship between cervical VEMP thresholds ($r = -0.56$, $p < 0.0001$) and surface area of the dehiscence was observed. No association between dizziness handicap and surface area was identified.

Conclusions—Among patients with confirmed SCD, ocular and cervical VEMP amplitudes, cervical VEMP thresholds, and air conduction thresholds at 250 Hz are significantly correlated with the surface area of the dehiscence.

Keywords

Superior Canal Dehiscence; VEMP; vestibular

INTRODUCTION

Superior canal dehiscence (SCD) is caused by an absence of bone covering the membranous labyrinth of the superior semicircular canal.¹ The clinical presentation of SCD is highly variable and can consist of auditory symptoms including hyperacusis, autophony, aural fullness/pressure, hearing loss, and tinnitus and vestibular symptoms including imbalance, and pressure or sound induced vertigo. While the mechanisms underlying the variable clinical symptoms are incompletely understood, it is generally believed that the bony dehiscence acts as a third window in the inner ear, shunting fluid motion away from the cochlea and altering the normal physiological function of the labyrinth.

In an effort to further elucidate the pathophysiology of SCD, recent studies have examined the relationship between dehiscence size and clinical variables. Intuitively, a large dehiscence would alter inner ear fluid dynamics to a greater extent than a small dehiscence. It follows that larger dehiscences would also be associated with more pronounced deviations in auditory and vestibular function. As it pertains to hearing, animal models have corroborated the notion that increased dehiscence size is associated with decreased auditory sensitivity.² In addition, human cadaveric models have shown that an increase in dehiscence size is associated with intracochlear sound pressure changes that are indicative of greater hearing loss.²⁻⁴ However, clinical studies have yielded conflicting data in regards to the impact dehiscence size has on audiologic testing. While some reports demonstrate that a larger dehiscence positively correlates with the size of the air-bone gap, other groups have failed to show a significant relationship between the two variables.⁵⁻¹⁰

In addition, the role of dehiscence size in vestibular testing outcomes, specifically vestibular evoked myogenic potential (VEMP) thresholds, has also been studied with inconsistent results. Niesten et al. and Pfammatter et al. reported that patients with larger bone defects demonstrated pathologically lowered cVEMP thresholds.^{5,11} Conversely, neither Saliba et al. nor Janky et al. were able to demonstrate a significant association between VEMP thresholds and dehiscence size.^{10,12}

Taken together, the impact of dehiscence size on audiometric and vestibular testing in patients with SCD remains unclear. Given that some studies measured dehiscence length radiographically and others intra-operatively, it is possible that these differences in measurement technique account for the discrepant results. Alternatively, current methods for measuring dehiscence characteristics may simply not be sensitive enough to parse out differences in microscopic anatomy between patients that would otherwise impact results. Surface area of dehiscence has been used as the measure of dehiscence size in animal studies; however, to date the impact of surface area on audiometric and vestibular testing in a clinical setting has not been previously studied. The authors hypothesize that surface area is a more accurate representation of actual size of the dehiscence when compared to dehiscence length. Accordingly, the aims of the study were to: 1) use CT image analysis techniques to measure the dehiscence area in patients with confirmed SCD, 2) examine the relationship between surface area and pre-operative audiometric and vestibular metrics.

MATERIALS AND METHODS

Subjects

Following institutional review board approval (151300), a retrospective chart review was performed evaluating all patients diagnosed with SCD between January 2011 and June 2015. Patients presenting with signs/symptoms suggestive of SCD and radiographic evidence of dehiscence were eligible for inclusion. The presence of unequivocal dehiscence on imaging was initially determined by a neuroradiologist, and subsequently confirmed by a neurotologist. Patients with a history of ear disease or prior temporal bone surgery were excluded as bony changes in these populations could bias measurements of dehiscence. In addition, patients who did not have complete audiograms or balance function testing that included both cervical and ocular VEMP testing were excluded.

Audiometric Testing

To assess hearing sensitivity and middle-ear status, air-conduction threshold testing was conducted at 250, 500, 1000, 2000, 4000, and 8000 Hz and bone-conduction threshold audiometry was conducted at 500, 1000, 2000, and 4000 Hz. Air- and bone-conduction thresholds at 500, 1000, 2000, and 4000 kHz were used to calculate four-tone pure-tone averages (PTAs). Overall air-bone gap (ABG) was calculated as air-conduction PTA minus bone-conduction PTA. Air bone gaps at individual frequencies were calculated by subtracting the bone-conduction threshold from air-conduction threshold at that specific frequency.

Vestibular Testing

All patients completed the dizziness handicap inventory (DHI) at the initial balance assessment.¹³ Patients were tested sitting upright for the oVEMP and in a semi-recumbent position for the cVEMP. Both oVEMP and cVEMP responses were obtained using a 95 dB nHL, 500 Hz tone burst.¹⁴ The tone burst had a two-cycle rise time, one-cycle plateau, and a two-cycle fall time and was gated with a Blackman-weighting function. Stimuli were presented at a rate of 5.1 per second.¹⁴ through ER3A (Etymotic Research) insert earphones coupled to the ears with soft compliant foam tips. The stimulus level was calibrated using a

Brüel and Kjaer (model 2250), Type 1 sound level meter coupled to the sound delivery system with a 2-cc coupler. The recording epoch for both oVEMP and cVEMP protocols was set to 100 msec, with a 10 msec pre-stimulus recording period and a 90 msec poststimulus recording period. Electrode impedances were kept to less than 5k Ω , and interelectrode impedances were always less than 3k Ω .

For cVEMP recordings, conventional disposable surface electrodes were applied to the middle third of each sternocleidomastoid muscle (i.e., representing the left and right active, or non-inverting amplifier inputs and the chin (reference-inverting)).¹⁴ The ground electrode was placed at Fpz. Artifact rejection was disabled. A band-pass filter of 10 to 1200 Hz was used during data collection. Amplification gain was $\times 5000$. A total of 150 single samples per averaging block were collected. Each averaging block was replicated at least once.

To record the oVEMP, subjects were instructed to direct their gaze at a visual target at a vertical elevation of ~ 30 degrees. Two-channel oVEMP recordings were obtained with the non-inverting electrodes placed infraorbitally at midline as close as possible to the lower margin (i.e. belly of the inferior oblique muscle) of the lower eyelid of both the ipsilateral and contralateral eye. The inverting electrodes were placed 2-3 cm inferior to the active electrodes. Amplification gain was $\times 100,000$. A total of 250 single samples per averaging block were collected. Each averaging block was replicated at least once.

Measurement of dehiscence length

While all patients had high-resolution temporal bone CT imaging, not all series included Pöschl views. In those patients that had high-resolution CT imaging with standard Pöschl views, the length of the dehiscence was measured in accordance with previously published reports. Specifically, a straight line between the bony ends of the dehiscence was measured in millimeters. If multiple dehiscences were present, the sum of the lengths of each dehiscence was considered the total dehiscence length. Measurements were made in duplicate by two independent neurotologists blinded to patient characteristics; the mean length of dehiscence was used for purposes of analysis.

Measurement of dehiscence surface area

Using pre-operative CT images from included patients, the superior semicircular canal was identified automatically using the labyrinth shape model-based segmentation algorithm proposed and validated by Reda et al.¹⁵ In this approach, the shape of the labyrinth segmentation is constrained to be similar to the shape of the labyrinth of individuals with normal anatomy. Thus, this approach permits accurate estimation of the shape of the superior semicircular canal even when a portion of the canal does not have a bony border in the CT image due to dehiscence. In 12 cases, small errors in the localization of superior canal were corrected manually using proprietary software designed for surface editing.

The surface area of the SCD was measured using a MATLAB (Mathworks, Natick, MA USA) script designed to detect the portion of the superior canal surface that is not encased in bone. To do this, each triangle in the superior canal surface is classified as normal or dehiscence. The sum of the surface areas of the dehiscence triangles is the total surface area of the dehiscence. A triangle was classified as dehiscence if the maximum image intensity

along a profile in the direction normal to the triangle is below a threshold value, indicating no bone is present at that triangle. The intensity threshold was determined semi-automatically for each image, where Otsu's method was used initially and then the threshold was adjusted as needed to achieve accurate dehiscence detection.¹⁶ The input to Otsu's method was the histogram of the image intensities in the region-of-interest within 400 voxels of the SCD. A neurotologist validated the final dehiscence area detected in each case. An example result is shown in Figure 1, where the dehiscence and normal areas of the SCD are shown in green and red.

Statistical analysis

Statistical analysis was performed using Prism 6 (GraphPad, La Jolla, CA). Data was assessed for normal distribution using D'Agostino-Pearson omnibus normality test. Normally distributed data was characterized with means and standard deviations, and nonparametric data was reported with medians and ranges. Spearman's rank correlation was used to correlate nonparametric data, with all significant values defined as $p < 0.05$.

RESULTS

A total of 53 subjects, 52.8% women, with a mean age 52.7 years (SD 10.8 years), were identified, with 31 subjects (58.5%) diagnosed with bilateral SCD. Thus, 84 SCDs were available for review (53.6% left ears). The mean dehiscence length was 3.33 mm (SD 1.39 mm), while the median dehiscence area was 1.44 mm² (0.068-8.23 mm²). There was a significant correlation ($r = 0.62$, $p=0.0002$) between dehiscence length and area (Figure 2). All correlations are listed in Table 1. There was no correlation between subject age and area ($r = -0.0078$, $p=0.96$).

Audiometric data were then analyzed. The median air- and bone-conduction pure tone averages were 21.9 dB HL (5 - 85 dB HL) and 15.0 dB HL (-3.8 - 57.5 dB HL), respectively. The median air-bone gap was 6.3 dB HL (-7.5 - 36.3 dB HL). Higher air conduction thresholds at 250 Hz weakly correlated with greater dehiscence area ($r = 0.25$, $p=0.02$) (Figure 3). Neither air nor bone-conduction thresholds at the remaining frequencies were associated with dehiscence surface area. In addition, no relation between the overall ABG and dehiscence area was observed. However, when individual frequency ABGs were correlated with the dehiscence area, the size of the ABG at 500 Hz directly correlated with dehiscence area ($r = 0.27$, $p=0.01$); no correlation was noted for the remaining frequencies.

When comparing oVEMP and cVEMP amplitudes, as well as cVEMP thresholds, to dehiscence areas, all three were significantly correlated ($r = 0.61$, $p<0.0001$; $r = 0.62$, $p<0.0001$; $r = -0.56$, $p<0.0001$) (Figure 4). Comparing DHI scores with surface areas, no correlation was observed ($r = 0.26$, $p=0.14$). Of interest though, of the 31 subjects that had bilateral superior SCD, 9 subjects stated "their worse ear" was actually the ear with the smaller dehiscence surface area.

In their computational model, Kim et al. reported that the average cross-sectional area of the canal was 1.0 mm².¹⁷ Thus, we dichotomized subjects with dehiscent surface areas above and below 1.0 mm², assessing the correlation between dehiscence area and oVEMP and

cVEMP amplitudes, cVEMP thresholds, and air-conduction thresholds at 250 Hz. In dehiscence areas larger than 1.0 mm², oVEMP and cVEMP amplitudes, and cVEMP thresholds were all significantly correlated ($r = 0.38$, $p=0.009$; $r = 0.56$, $p<0.0001$; $r = -0.54$, $p<0.0001$), while air-conduction thresholds at 250 Hz were not significantly correlated ($r = 0.28$, $p=0.051$). In dehiscence areas smaller than 1.0 mm², only cVEMP amplitudes were significantly correlated ($r = 0.43$, $p=0.018$).

DISCUSSION

Available data regarding the relationship between SCD size and objective measures of auditory and vestibular dysfunction in patients is conflicting. The majority of clinical studies use dehiscence length as a surrogate marker for dehiscence size. By subjecting reformatted CT images of SCD patients to segmentation analyses, we were able to calculate the surface area of the bony dehiscence overlying the superior canal. This allowed comparisons of dehiscence surface area to both auditory and vestibular measures. Our results demonstrate that dehiscence surface area is strongly correlated to oVEMP and cVEMP amplitudes, and weakly correlated with air-conduction pure-tone thresholds at 250 Hz and ABG at 500 Hz. Further, dehiscence area strongly correlated inversely with cVEMP thresholds.

Several reports have measured dehiscence length radiographically and intraoperatively, with distances ranging from 0.6-8.5 mm, with means between 3.50 - 4.68 mm.^{7,8,10,11,18-20} As there is no validated technique for measurement of the dehiscence, a variety of methods have been described. Radiographic techniques include a straight line measurement between bony edges of the dehiscence on reformatted Pöschl views, a curved measurement made after reconstruction of the canal⁵, and a straight line measurement made of sagittal imaging sequences.⁹ There are a few reports assessing dehiscence area intraoperatively, with mean areas of 2.67 mm² and 3.19 mm².^{12,21} Intraoperative measurement of surface area dehiscence can be extremely challenging, particularly in smaller dehiscences. To our knowledge, this is the first study to radiographically measure dehiscence surface area. As expected, a strong correlation was noted when comparing dehiscence length to surface area within our cohort. Our reported mean dehiscence length (3.33 mm) and dehiscence area (1.44 mm²) are smaller than previously reported values. One potential reason for this difference is selection bias; while some studies only included operated patients, we also included patients managed without surgery.^{10,12,21} Alternatively, our methodology may be superior in accurately measuring smaller dehiscences.

Several reports have investigated the relationship between the dehiscence size and clinical symptoms, audiometric and vestibular metrics, and even vestibular compensation measures.^{4,6,7,9,11,12,19,21,22} Pfammater et al. noted that a larger dehiscence correlated with vestibulocochlear manifestations, while other studies found no associations.^{5-7,9,11} And though Niesten et al. did not find any correlation between dehiscence length and clinical signs and symptoms, when they grouped patients together based on their symptom profile, patients with auditory symptoms had significantly longer dehiscences starting closer to the ampulla compared to those without auditory complaints.⁵

The relationship between dehiscence size and audiometric results has been explored in both clinical studies and computational models of chinchilla and human temporal bones. It was initially theorized that larger dehiscences would lead to lesser impedances and more low-frequency conductive hearing loss.²³ Our data did not demonstrate a significant correlation between dehiscence area and any bone-conduction pure-tone threshold, while noting a weak correlation between dehiscence area and air-conduction pure-tone threshold at 250 Hz. This is in agreement with previously published reports when assessing the dehiscence length.⁵

In regards to the ABG, the majority of studies have demonstrated a significant correlation between dehiscence length and ABG, particularly for lower frequencies.^{5,8,24} We also investigated the relationship the dehiscence size has with the ABG. While overall ABG did not correlate with dehiscence size in our cohort, analysis of ABG at individual frequencies demonstrated that ABG was directly related to SCD surface area at 500 Hz, supporting prior findings. It is generally accepted that SCD manifests conductive hearing loss primarily at lower frequencies.^{5,6,17,22} For this reason, it is not surprising that a significant relation between ABG and dehiscence size was only noted at 500 Hz.

Some groups have suggested that a correlation between dehiscence size and hearing might exist within a restricted range of dehiscence sizes. Rosowski et al. theorize that a dehiscence would have to be larger than 3 mm to produce an air bone gap.²³ Conversely, computational models suggest that when the dehiscence area becomes larger than the cross-sectional area of the semicircular canal, further increases in dehiscence area are insignificant.^{2,17} Re et al. postulated that dehiscences larger than 5 mm are not associated with symptoms, since large dehiscences allow the overlying dura to compress the membranous superior canal, preventing endolymphatic flow and reflex activation.¹⁸ Using cadaver temporal bones, Pisano et al. noted that in some ears, smaller dehiscences (0.5 mm) lead to greater decreases in scala vestibuli pressures as compared to larger dehiscences.³ They speculated that a lack of consensus exists between dehiscence size and air-bone gaps because there is a monotonic relationship between the dehiscence size and pure-tone thresholds.³

Thus we sought to examine if increases in the dehiscence area to sizes larger than the cross-sectional area of the semicircular canal impacted audiometric and vestibular test results. To accomplish this, we dichotomized patients to those with dehiscence areas above and below 1.0 mm², the average cross-sectional area that was previously reported by Kim et al.¹⁷ In the cohort with dehiscence areas above 1.0 mm², a trend toward higher air-conduction pure tone thresholds at 250 Hz in larger dehiscences was observed, but this failed to reach statistical significance (p=0.051). This lack of significance could be due to a small sample size. No significant relationship was observed when analyzing air-conduction thresholds at 250 Hz within the smaller dehiscence group. Further *in vivo* studies with larger cohorts are needed to clarify the impact of large dehiscent surface areas on low frequency audiologic performance.

The association between vestibular testing, specifically VEMP amplitudes and thresholds, and dehiscence size has received considerable attention in the literature. Rajan et al. found that with longer dehiscences, lower stimuli frequencies were required to provoke a nystagmic response during electronystagmography.¹⁹ In addition, several groups have

reported significant correlations between longer dehiscences and lowered cVEMP thresholds.^{5,11} As for cVEMP and oVEMP amplitudes, there are conflicting reports regarding the correlation between dehiscence size and amplitudes.^{5,12} Our findings demonstrate a strong positive correlation between surface area and both cVEMP and oVEMP amplitudes. In addition, a strong inverse relationship between cVEMP thresholds and dehiscence area was noted. Subgroup analysis of larger ($> 1 \text{ mm}^2$) dehiscences demonstrated similar findings; namely cVEMP amplitudes, cVEMP thresholds, and oVEMP thresholds all correlated with surface area of the dehiscence. However, in the group with smaller dehiscences, cVEMP thresholds was the only variable that correlated with surface area. Taken together, these findings suggest that cVEMP amplitude may be most sensitive to changes in surface area across the entire spectrum of dehiscence areas.

Several limitations must be considered when interpreting our results. Though many subjects within this reported population underwent surgical repair, the length or area of the dehiscence was not measured intraoperatively, preventing validation of our segmentation processing and analyses. Although intraoperative validation of the radiographic measurements would be ideal, the authors suspect that intraoperative manual measurements would demonstrate poor reliability and reproducibility, particularly in cases of a small dehiscence. Furthermore, CT images were obtained at a variety of imaging centers, leading to variability in the quality of scans. This bias was minimized by excluding scans in which segmentation analysis could not be performed. Nevertheless, the segmentation processing is still limited by the accuracy and resolution of the source CT images for included studies. Further, we recognize that previous studies have highlighted that volume averaging may lead to a misleading dehiscence appearance, especially for defects under 2 mm.²⁵ We feel that diagnosis of a clear dehiscence with subsequent confirmation by a neurotologist limits, but does not eliminate, the potential bias introduced by volume averaging. Future studies are ongoing in which intraoperative dehiscence measurements are taken to validate our segmentation analyses.

CONCLUSION

Using internally developed and previously validated software to perform segmentation analysis of reformatted temporal bone CT images of patients with unequivocal SCD, we report a median surface area of dehiscence of 1.44 mm^2 . The SCD area demonstrated significant positive correlations with air-conduction thresholds at 250 Hz, ABG at 500 Hz, oVEMP and cVEMP amplitudes, while a significant inverse relationship was observed when comparing dehiscence area and cVEMP thresholds. There was no correlation between dehiscence area and age, bone-conduction thresholds, the remaining air-conduction thresholds, and frequency specific ABGs greater than 500 Hz.

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Figure 1. 3D (left) and coronal (right) view of the SCD. The normal and dehiscence regions of the superior semicircular canal are shown in red and green, respectively

Figure 2.
Dehiscence area plotted against radiographically measured dehiscence length.

Figure 3.
Dehiscence area plotted against air-conduction thresholds obtained at 250 Hz.

Figure 4. Dehiscence area plotted against oVEMP amplitudes (A), cVEMP amplitudes (B), and cVEMP thresholds (C).

Table 1

Significant values are bolded and underlined.

Correlation with Dehiscence Area	Rho	p
Dehiscence Length	0.62	<u>0.0002</u>
Age	-0.008	0.96
Overall Air-Conduction Thresholds at 250 Hz	0.25	<u>0.02</u>
Overall oVEMP Amplitudes	0.61	<u><0.0001</u>
Overall cVEMP Amplitudes	0.62	<u><0.0001</u>
Overall cVEMP Thresholds	-0.56	<u><0.0001</u>
DHI	0.26	0.14
Air-Bone Gap PTA (500, 1000, 2000, 4000 Hz)	0.13	0.25
Air-Bone Gap at 500 Hz	0.27	<u>0.01</u>
Air-Bone Gap at 1000 Hz	-0.22	0.051
Air-Bone Gap at 2000 Hz	0.08	0.49
Air-Bone Gap at 4000 Hz	-0.009	0.25
Dehiscence Areas 1.0 mm ²		
Air-Conduction Thresholds at 250 Hz	0.28	0.05
oVEMP Amplitudes	0.38	<u>0.01</u>
cVEMP Amplitudes	0.56	<u><0.0001</u>
cVEMP Thresholds	-0.54	<u><0.0001</u>
Dehiscence Areas < 1.0 mm ²		
Air-Conduction Thresholds at 250 Hz	-0.18	0.31
oVEMP Amplitudes	0.14	0.48
cVEMP Amplitudes	0.43	<u>0.02</u>
cVEMP Thresholds	-0.13	0.61