Functional Correlations of Tympanic Membrane Perforation Size

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Objective: The correlation between tympanic membrane perforations and hearing loss was studied.

Study Design: Prospective data from 220 patients, who underwent primary surgery for simple chronic otitis media with a perforated eardrum, were analyzed.

Setting: Tertiary referral center.

Patients: One hundred fifty-one patients with 155 eardrum perforations, which were checked for correct diagnosis, normal middle-ear status, and integrity of the ossicular chain, were included.

Interventions: All patients underwent primary myringoplasty.

Main Outcome Measures: Preoperative conductive hearing loss due to eardrum perforations.

Results: Hearing loss shows a linear relationship with increasing eardrum perforation size. Umbo involvement shows a worsening of the hearing by 5 to 6 dB ($p < 0.0001$). The least impact of a perforation is seen at the resonance frequency of 2 kHz. An "inverted V-shape" pattern, above and below 2 kHz, of the air-bone gap is a consistent finding. If the air-bone gap exceeds this pattern, additional pathology behind the eardrum perforation must be assumed and addressed.

Conclusion: We propose using standardized photographs or drawings to document preoperative perforation sizes. A linear relationship between the size of a perforation and the conductive hearing loss does exist. Umbo involvement at the perforation margin may worsen the hearing by 5 to 6 dB, whereas the position of the perforation itself does not play a role. The least impact of a perforation is seen at the resonance frequency of 2 kHz. An "inverted V-shape" pattern, above and below 2 kHz, of the air-bone gap is a consistent finding. If the air-bone gap exceeds this pattern, additional pathology behind the eardrum perforation must be assumed and addressed.

Key Words: Conductive hearing loss—Frequency of hearing loss—Location—Resonance frequency—Relation between air-bone gap and perforation size—Tympanic membrane perforation—Umbo involvement.

the literature. Tools for measuring tympanic membrane perforations were studied, and a simple method will be proposed.

MATERIALS AND METHODS

Recruitment of Patients
Using a prospective database (Innoforce ENTstatistics, www.innoforce.com), a search was performed for all patients who underwent primary myringoplasty for chronic otitis media simplex at the Kantonsspital Luzern, Switzerland. A preoperative audiogram and a perioperative drawing or otoscopic picture and the operating report had to be available. Overall, 220 primary operations were checked for correct diagnosis, normal middle-ear status, and integrity of the ossicular chain. Sixty-five of 220 TMP (29.5%) were rejected from the study because of middle-ear pathology (e.g., granulation tissue, malleus adhesive to the promontory, synchiae at the level of the ossicular chain) or bad quality of photographs or drawings, leaving 155 TMP on which all statistical calculations were performed. The study was approved by the institutional review board of the Kantonsspital Luzern.

Analysis of the Data

Method of Measuring Tympanic Membrane Perforation Sizes
Fifteen percent of the 155 included patient files had good perioperative photographs, and all had surgical drawings. After validating the correct correlation between surgical drawings and preoperative photographs (see below), we chose to use consistently the perioperative drawings, made by 3 senior otologists. They were all measured with the Cyclops Auris software (generously provided by Dr. Sady da Costa, Porto Alegre, Brazil). After reviewing the literature, this computational semiautomated and user-friendly software was selected as it measures the relative sizes of the TMP to the whole eardrum as well as their relative location in percentages (9,10), (Fig. 1).

Validation of TMP Drawings Versus Photographic Records
Because not all patients had accurate preoperative photographs, a separate study was performed within our department to check the accuracy and validity of perioperative drawings in comparison to preoperative endoscopic pictures of TMP. Otoscopic photographs of tympanic membrane perforations of different sizes, sites, and shapes were showed to 14 clinicians of different sizes, sites, and shapes were showed to 14 clinicians of different experience level of the observer as experienced otologists and junior ENT clinicians rated similarly.

Correlation Between Clinical Assessment of TMP and Computer Data
The correlation between the clinical assessment of TMP and our computer measurements was determined. The dataset was divided into 4 categories of relative perforation sizes. They were chosen according to our daily clinical judgments. The first category contains patients with relative TMP sizes less than 2.5%, which corresponds to a microperforation. The second category contains patients with relative TMP sizes between 2.5% and 12.5%, which corresponds to a one quadrant TMP. The third category contains patients with relative TMP sizes between 12.5% and 32.5%, consisting of kidney-shaped TMP, and finally, the last category contains all patients with relative TMP sizes larger than 32.5%, including all subtotal TMP. These cutoffs were made after careful examination of the shapes of TMP and our measurements, irrespective of patient numbers within each category.

Audiometric Data Analysis and Statistical Analysis
Using the Innoforce ENTstatistics software, the preoperative air-bone gap (ABG) was calculated for each patient, for the whole patient group and for each category. The ABG was calculated for each frequency from 500 to 4,000 Hz, as well as for the pure tone average (PTA) from 500 to 4,000 Hz. For one of the statistical analysis, the patient group was subdivided into patients with normal bone conduction (BC) and abnormal (>20 dB) BC thresholds on preoperative audiogram. Statistical calculations were performed using JMP Statistical Discovery Software 8.0 (SAS Institute Inc., Cary, NC, USA). The relation between the perforation size, mean ABG, average ABG for each frequency, and each size group were studied using regression methods. A linear model, estimated by least squares, was fitted through the points. The least-squares method minimizes the sum of squared differences from each point to the line. p < 0.05 was considered statistically significant.

The relative position measurements of the TMP and umbo involvement were used to evaluate the influence of position of TMP on hearing. Using the Innoforce ENTstatistics database, a search was performed within our dataset on patients with TMP restricted for 90% to the anteroinferior quadrant, as well as the posteroinferior quadrant. The same was done for TMP restricted for 90% to the anterior and posterior half of the eardrum. The number of patients with TMP in a certain quadrant was counted, and the PTA for these patient subgroups was calculated and compared for statistical significant differences.

RESULTS

General Data
Of 151 patients (155 TMP), there were 81 men (54%) and 70 women (46%) with an average age of 38 years (7–89 yr). Size measurements showed perforation sizes from 0.34 to a maximum of 67%, which were divided into 4 size categories. BC was normal in 92 patients (95 eardrums) and abnormal with mainly presbyacusis in 59 patients (60 eardrums). In total, 35 of 155 TMP showed umbo involvement, divided over the perforation size categories.

Validation of TMP Drawings Versus Photographic Records
The results of the internal study are visualized in Figure 2. There is a strong correlation between the relative sizes of the TMP of the otoscopic images and their corresponding drawings. One numeric estimation was asked, significant overestimation is apparent with increasing TMP size. Accuracy seemed not to depend on the experience level of the observer as experienced otologists and junior ENT clinicians rated similarly.
**Relation Between TMP Size and Hearing Loss**

Figure 3 shows the outcome of all the measurements. With increase in TMP size, the mean ABG increases. We found a clear distribution of umbo involvement over all the size categories. The relation between TMP size and mean ABG is linear (Fig. 3), with the following formula: $y = (0.35 \times p) + 10.84$, with $p$ being the TMP size. $R^2$ is 0.43, which means that 43% of the variability is explained by the model. Figure 4 shows the relationship between tympanic membrane perforation size and hearing loss for each frequency. At each frequency, a clear increase of the hearing loss is seen, as the size of the perforation gets bigger. Figure 5 gives an overview of the linear relationship for each frequency between the perforation size and the ABG from 500 to 4,000 Hz and the mean ABG of all frequencies. It is clear that 2,000 Hz is the most stable frequency with only minimal change in ABG, whereas 4,000 Hz is the most subject to changes in perforation size.

**Relation Between Hearing Loss, Frequency, and Umbo Involvement**

The ABG for each frequency was plotted for the whole patient group and for the 4 size categories, with a 95% confidence interval (CI). In every size group, the ABG
decreases with an increase in frequency until 2 kHz. Above 2 kHz, there is an increase in ABG with increasing frequency. There is a consistent “inverted V shape” of the audiogram with the largest ABG found at 0.5 kHz for every size category and the smallest at 2 kHz. Frequencies above 2 kHz again show a bigger ABG (Fig. 6, A and B).

The significance of umbo involvement on hearing loss was studied for individual frequencies and on the PTA. There is a significant difference (varying from 5 to 12 dB) for the ABG at all frequencies and, in a multivariate model (combined with perforation size), remained significant at all frequencies. Overall, this hearing loss due to umbo involvement was 5.5 dB for the whole group. However, the effect of the umbo involvement was much smaller than the effect of the perforation itself.

Relation Between Position of TMP and the Hearing Loss

When comparing the ABG for each quadrant, no significant difference became obvious (Fig. 7). In addition, all perforations restricted to one quadrant or one-half of the eardrum were grouped. When comparing one quadrant perforations in the anteroinferior quadrant versus the posteroinferior quadrant, there was no significant difference in mean ABG ($p = 0.93$). The same is true for one-half

![Diagram 1](image1.png)

**FIG. 3.** Mean air-bone gap in decibels from 500 to 4,000 Hz versus tympanic membrane perforation size. The solid line represents the linear regression curve with the formula; the dotted lines correspond to the 95% CI.

![Diagram 2](image2.png)

**FIG. 4.** Relationship between tympanic membrane perforation size and hearing loss for each frequency: A, The ABG in decibels for 500 Hz for every size category, with a 95% CI. B, ABG for 1,000 Hz for every size category, with a 95% CI interval. C, ABG for 2,000 Hz for every size category, with a 95% CI interval. D, ABG for 4,000 Hz for every size category, with a 95% CI interval.

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perforations ($p = 0.69$). The difference between high and low frequencies also was checked and showed no difference in ABG related to the location of the TMP.

**Relation Between Bone Conduction and Hearing Loss Because of TMP**

The BC levels were checked for influence on the ABG at each frequency. There is no significant difference between the group with normal BC and the one with abnormal BC, at each frequency, showing that a TMP causes a conductive hearing loss without influencing the BC. There was a significant increase in BC thresholds with age, as can be expected because of presbyacusis; however, there was no relation between age and size of the ABG in TMP.

**DISCUSSION**

Evaluating patients with COM includes a careful otoscopic assessment of the perforation size, location, and an estimate of its effect on sound transmission. Before checking the patient’s audiogram, the otologist should be able to predict the expected hearing impairment from his clinical judgment. If the audiogram does not correspond

FIG. 5. Summary of linear relationship for each frequency between the perforation size and the mean ABG from 500 to 4,000 Hz; 2,000 Hz shows the least increase in ABG with increasing perforation size, and 4,000 Hz shows the most increase in ABG with increasing perforation size.

FIG. 6. A, The mean ABG per frequency for the whole patient group showing an overall inverted V shape. B, The mean ABG per frequency for every size category showing a clear inverted V shape within each group. The ABG for each frequency or the “inverted V” gets bigger with increasing size of the tympanic membrane perforation.
observers showed similar accuracy of TMP drawings. The objective computerized analysis of a perforation size from a surgeon’s drawing seems to be a correct and pragmatic methodology.

Size of TMP and Hearing Loss

Previous studies comparing hearing loss and perforation size used air conduction (AC) levels or ABG. Because elderly patients often present with presbyacusis, AC levels give a wrong estimate of the high-frequency impairment because of the perforation itself. Most studies concur that conductive hearing worsens with increasing perforation size; however, a linear relationship remained debatable. As shown in this study, a linear relationship between the mean ABG 0.5 to 4 kHz and the size of the tympanic membrane perforation could be verified. This linear regression line and the 95% CI are depicted in Figure 3. A similar linear regression line was observed for each frequency (Fig. 4). Furthermore, if the 4 most frequent types of perforations were sorted out as groups, a similar pattern was found.

Frequency-Dependent Hearing Loss in TMP

The focus of previous studies has been on frequencies below 2 kHz. Animal experiments in cats revealed greater hearing loss in the lower frequencies, also increasing in magnitude with increasing size of the TMP (2,3,6). Anthony et al. examined 103 patients with TMP and described a pronounced hearing loss in the lower frequencies, gradually becoming less in the high frequencies (4). Ahmad and Ramani (5) performed a clinical study on 70 patients and confirmed a greater hearing loss in the lower frequencies increasing with the size of the perforation. Conversely, Austin (13) speculated that hearing losses due to perforations of the tympanic membrane were unrelated to frequencies. Our results from 155 TMP revealed a consistent frequency pattern, similar to an “inverted V shape” of the audiogram with a turning point around 2 kHz. Below 2 kHz, the ABG is larger for the lower frequencies, and above 2 kHz, the ABG gets bigger again in the higher frequencies. There are minimal changes in ABG at 2 kHz, independent of the size of the TMP. At 0.5 and 4 kHz, the changes are maximal, with greater variability with increasing size of TMP. Recent studies by Voss et al. (19–21) disclosed the same “turning point” around 2 kHz on cadaver temporal bones. The impairment of sound transmission was greatest at the lowest frequencies and decreased toward zero at 1 to 2 kHz with further sound transmission loss above 2 kHz typically less than 10 dB. They did not comment on this high-frequency observation. Throughout the whole study, our data confirmed a consistent turning point at 2 kHz, even when subdividing the entire group into size categories, bone conduction issues, umbo involvement, or other variables. Considering anatomy and physiology of the outer ear canal and the middle ear, 2 kHz is known as their dominant resonance frequency. Lokberg et al. (22) have calculated the resonance frequency of the eardrum to be around 2 kHz, and Stasche et al. (23) found the highest umbo displacement of the tympanic

**FIG. 7.** Statistical analysis revealing no significant difference between the conductive hearing loss at different locations of the perforation. The diagram shows the incidence of a certain quadrant being involved, whenever the tympanic membrane in general is perforated. This can be restricted to one quadrant or involve several quadrants.
membrane in a cadaver temporal bone study at 2 kHz and the resonance frequency between 2 and 3 kHz. Gyo et al. (24) discovered the highest lever ratio of the ossicular chain at 2.2 kHz using laser Doppler vibrometry. We therefore conclude that the human middle ear has the least loss of sound transmission (or best hearing) around 2 kHz, no matter which pathology is at hand. In contrast with the stability and consistency found for 2,000 Hz, there is a maximum of variation found at 500 and 4,000 Hz in our patient group. These frequencies were the most sensitive to changes within the eardrum (Fig. 8).

The Influence of Umbo Involvement in a TMP on the Hearing Loss

Whereas most studies do not mention or even exclude malleus or umbo involvement in chronic otitis media, Ahmad and Ramani (5) demonstrated a clear influence of malleus involvement on the hearing. They made obvious that hearing got worse once the malleus was involved in the TMP. Voss et al. (19) mentioned a 5-dB hearing loss in case of reduced coupling of the tympanic membrane to the ossicular chain. It would be a false presumption to believe that umbo involvement only occurs in large (subtotal) perforations. Our data show a clear distribution of umbo involvement in 3 size categories, but it is obvious that the bigger the TMP, the more likely the umbo is involved. Because of the conical shape and the radial fibers in the eardrum, the sound is directed toward the umbo of the malleus. Gundersen (25) has shown that there is a difference between the acoustical driving force at the umbo and at the neck of the malleus. All these data align with our findings that umbo involvement in TMP worsens the hearing significantly with 5.5 dB on mean ABG, meaning that whenever the umbo is involved, 5.5 dB can be attributed to the loss of coupling, and the rest of the ABG is caused by the fact that there is a perforation in the eardrum.

The Influence of Position of a TMP on the Hearing Loss

Since the earliest experiments on TMP, there has been debate on whether the position of TMP has an influence on the hearing loss. Almost every textbook still mentions worse hearing if the posterior half is involved. Reviewing human studies, Anthony and Harrison (4) and Ahmad and Ramani (5) supported this idea, as have many others since then. However, in most studies, position was assigned or estimated but never exactly measured, as can be done with the Cyclops Auris software (Fig. 7). They are as many studies contradicting this “location” theory. Voss et al. (7,20) made it clear with several studies that the theory of sound pressures acting directly onto the round and oval windows in posterior TMP and, thus, inhibiting pressure difference between the windows has only a very small influence on the hearing loss caused by TMP. Our data show no significant difference of location of TMP on the hearing loss, when comparing anteroinferior and posteroinferior quadrant perforations or when comparing anterior half and posterior half perforations and thus affirm the latest data. We feel that the phase cancellation theory must be abandoned once and for all.

The Influence of Middle Ear and Mastoid Volume on the Hearing Loss Caused by TMP

Recently Voss et al. (7,21) introduced the idea of middle ear and mastoid volume as an influencing factor on hearing loss in chronic otitis media. Several studies were performed using cadaver temporal bones and theoretical models to calculate the influence of a varying mastoid volume on hearing loss assuming that the middle ear volume is almost constant. They state that, for equal sizes of TMP, the bigger the mastoid volume, the smaller the conductive hearing loss and vice versa. This idea is based on a model, which shows that the increased sensitivity (or better hearing) found around the 2-kHz region shifts toward a lower frequency region (e.g., 1,500 Hz) with an increase in mastoid volume. This means that hearing loss should change with varying mastoid volumes for an equal TMP size. How to accurately measure middle ear and mastoid volume in patients is still a matter of debate. Serial sections of CT scans may be used; however, the exact volumetric measurements are tedious to obtain (personal study, not published), and opacifications (e.g., effusion or granulation tissue) within the pneumatized air cells

FIG. 8. Impact of increasing perforation size on hearing at 4,000 Hz.
may vary over time. Tympanometry has been suggested to predict the total volume. Mehta et al. (8) conducted a clinical study, using tympanometry to determine middle ear and mastoid volume in TMP, which confirmed the results found by Voss et al. (21). For the same size of a perforation, they found that “the bigger the mastoid volume, the smaller the hearing loss.” In our current study, this parameter was not included as CT scans or volume recordings of tympanometry were not adequately available. It also appears (Ahn et al. [26]) that tympanometry is overestimating the true volume and that some tympanometry devices do not measure more than 3 to 5 ml of volume (Mehta et al. [8]).

The impact of “real” volume and “acoustic relevant” volume on hearing still remains debatable and needs to be further examined.

**CONCLUSION**

Previous studies do not adequately measure but rather guess the perforation size or use inadequate quadrant rules to describe a tympanic membrane perforation. We propose to use standardized endoscopic photographs or at least well performed drawings to document preoperative perforation size. Surgical drawings seem to correlate well with photographs.

The impact of a “simple” perforation (with an intact ossicular chain) on hearing should be predictable by the otologist. A linear relationship between the size of a perforation and the conductive hearing loss does exist as a general rule. The involvement of the umbo at the perforation margin may worsen the hearing by 5–6 dB, whereas the position of the perforation itself does not play a role. The impact of middle ear and mastoid volume on conductive hearing loss needs further evaluation.

The least impact of a perforation is seen at the resonance frequency of 2 kHz. Above and below 2 kHz, an “inverted V shape” of the air-bone-gap is a consistent finding. If the air-bone-gap does not follow this pattern and exceeds 16 dB for one-quadrant perforations, 25 dB for kidney-shaped TMP and 37 dB for subtotal TMP at 4 kHz, additional pathology behind the tympanic membrane perforation must be assumed and addressed. An evaluation tool for TMP is provided in pdf format (see pdf diagram, Supplemental Digital Content 1, available at http://links.lww.com/MAO/A102, which can be used in daily use to evaluate the expected hearing loss of a TMP).

**REFERENCES**
