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The Profile of Otoacoustic Emissions and Multifrequency Tympanometry in Otosclerotic Patients Undergoing Two Types of Stapes Surgery: Small Fenestra and Microtraumatic Stapedotomy

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Background: Otoacoustic emissions (OAEs) are influenced in otosclerosis. The aim of the current study was to investigate the profile of transient evoked (TEOAEs) and distortion product otoacoustic emissions (DPOAEs) in association with multifrequency tympanometry measures in otosclerotic patients undergoing 2 types of stapes surgery: small fenestra and microtraumatic stapedotomy.

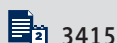
Material/Methods: A retrospective analysis of prospectively collected data was conducted evaluating 51 otosclerotic patients and 50 normal hearing subjects. Small fenestra and microtraumatic stapedotomy were performed in 27 and 24 patients, respectively. Pure tone audiometry (PTA) was always measured. Detection of TEOAEs and DPOAEs at 5 frequency steps (1, 1.4, 2, 2.8, and 4 kHz) preoperatively and at 2 and 5 months postoperatively, stratified by the type of surgery, represented the main goal of the study. Resonant frequency derived by multifrequency tympanometry was also evaluated.

Results: All patients demonstrated improvement in hearing level postoperatively, with significant closure of air-bone gap on PTA. Resonant frequency values returned to normal after microtraumatic stapedotomy but were exceedingly decreased following the small fenestra technique. The detection of both TEOAEs and DPOAEs was improved, but when the detection was stratified by the tested frequencies, significant increase in the number of patients with detectable OAEs was observed, mainly during testing at 1 and 1.4 kHz.

Conclusions: Otosclerotic patients exhibited improvement in the detection of OAEs, particularly at low frequencies, after both procedures. Resonant frequency was normalized following the microtraumatic stapedotomy, whereas it is over-decreased after the small fenestra technique.

MeSH Keywords: **Audiometry • Hearing Loss, Conductive • Otosclerosis • Stapes Surgery**

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Background

Otoacoustic emissions (OAEs) represent an audiofrequency signaling into the ear canal produced in the cochlea and transmitted through the ossicular chain and tympanum. They are believed to originate from vibrations generated by healthy outer hair cells [1]. According to Kemp's proposal, a biomechanical amplifier within the organ of Corti seems to underlie OAEs' properties [2]. Aside from spontaneously occurring otoacoustic emissions, OAEs can also be evoked by acoustic stimulation. Transient evoked (TEOAE) and distortion product (DPOAE) otoacoustic emissions are the 2 types of OAEs that are commonly measured clinically, mainly for hearing evaluation in newborns, children, and adults [3].

TEOAEs are elicited with very brief, transient sounds, such as clicks or tone bursts, presented to the ear at an intensity level of 80 dB SPL. TEOAEs are generally recorded over the frequency range of 500 to about 4000 Hz. They are detectable essentially when hearing threshold is better than 30dB and they are frequently used for hearing screening in newborns, noise-exposed workers, and patients taking ototoxic drugs [4,5].

DPOAEs are elicited with sets of 2 pure tone frequencies (abbreviated as f2 and f1), which are closely spaced and presented simultaneously at moderate intensity levels – mainly at 55 and 65 dB SPL, respectively. The highest amplitude at the frequency 2f1–f2 is used principally for routine audiological evaluations [6].

Although otoacoustic emissions preferentially reflect the functional status of the cochlea [7], they may undergo changes due to disorders of the external and middle ear structures, because their interpretation depends on the acoustic stimulus transmission, both towards the inner ear and retrograde. Certain diseases of the middle ear may decrease the amplitude of otoacoustic emissions or even obliterate responses. Otosclerosis is a primary localized disease of the bony otic capsule, which has a predilection for the oval window and leads to fixation of the stapedial footplate within the oval window niche [8]. The profile of OAEs could therefore be altered in otosclerotic patients.

Additionally, it has been reported that resonance in the external and middle ear has an important role in sound transmission. Resonant frequency represents the middle ear's frequency at which the effects of mass and rigidity cancel each other. Many studies suggest that otoacoustic emissions are best detected around this frequency level, as well as in subjects with moderate middle ear mobility [9]. Multifrequency tympanometry enables the recording of admittance across a wide range of probe tone frequencies, providing an estimate of the middle ear resonant frequency, which has potential diagnostic value in pathologies that increase middle ear stiffness, like otosclerosis [10].

Limited data is available in the literature about the effect of stapes fixation on the profile of otoacoustic emissions and resonant frequency measures derived by multifrequency tympanometry. Furthermore, no data exists about the comparative auditory outcome after small fenestra stapedotomy and a microtraumatic modification [11] of the procedure. For all of these reasons, we attempted to evaluate the impact of otosclerosis and the 2 types of surgical intervention in the profile of transient evoked and distortion product otoacoustic emissions, as well as in the values of resonant frequency, derived by multifrequency tympanometry.

Material and Methods

Fifty-one patients (17 men, 34 women) with mean age of 48.1 ± 11.1 years old, suffering from otosclerosis were included in the study during a 4-year period (2007–2010), after institutional review board approval. Fifty normal-hearing subjects with mean age of 39.2 ± 11.7 years were compensated for their participation and formed the control group. No patient had history of metabolic disease, exposure to noise, or use of ototoxic drugs. All patients underwent stapes surgery in the form of stapedotomy. Small fenestra stapedotomy was performed in 27 cases (13 left and 14 right ears) and a microtraumatic modification of the procedure [11] was performed in 24 patients (15 left and 9 right ears). The results were evaluated at routine follow-up intervals 2 and 5 months after surgery.

Pure tone audiometry (PTA), transient evoked otoacoustic emissions (TEOAEs), distortion product otoacoustic emissions (DPOAEs), and multifrequency tympanometry (MFT) were performed in all patients. The same tests were performed in the control subjects, who also fulfilled the same exclusion criteria. All normal-hearing subjects had auditory thresholds equal to or better than 25 dB, a type A tympanogram, and normally elicited ipsilateral acoustic reflexes.

The external acoustic meatus and tympanic membrane were first inspected with an otomicroscopic examination and were found normal in all cases. All audiological tests were performed in sound booth.

Pure tone audiometry (PTA) was performed at 250, 500, 1000, 2000, 4000, and 8000 Hz using a diagnostic AD226 Interacoustics® audiometer. Additionally, admittance tympanometry (Ymt) at a probe frequency of 226 Hz and ipsilateral acoustic reflexes using stimuli at 500 Hz, 1000 Hz, and 2000 Hz were tested using an Interacoustics® AT235h middle ear analyzer.

Assessment of the middle ear resonant frequency was achieved using samples for multifrequency tympanometry testing, taken

with an external ear microphone probe using a Welch Allyn – GSI 33 (version 2) middle ear analyzer. This device uses 3 tone frequencies (226, 678, and 1000Hz) in the immittance probe. Tympanometric measures are automatically performed at 50 daPa/s and the probe frequency can vary automatically from 250 to 2000 Hz at 50 Hz intervals in the initial pressure. A printer incorporated into this system recorded the results. Measures of immittance components and phases were stored in the device memory. The probe tube was inserted at 27 mm from the tragus and 8 mm from the tympanic membrane. First, a tympanogram in acoustic admittance (Ya) mode at a probe frequency of 226 Hz was recorded and peak data were noted. A second scan at the tympanometric peak (Ya) pressure at 226 Hz was presented, and phase and component measures were again stored. The differences in component (ΔY , ΔB , and ΔG) and phase values ($\Delta \theta$) among the first and second frequency scans were then calculated and presented on the monitor screen according to frequency variations (from 250 Hz to 2000 Hz). The middle ear resonant frequency was automatically shown by the cursor on the screen; a new tympanogram was always performed at the resonant frequency to check the type of the curve.

Both TEOAE and DPOAE testing took place using a DP Echoport ILO 292 USB analyzer, which delivered the complete range of single-probe clinical tests through ILO V6 software. Software was installed in a desktop computer that used Microsoft Windows XP® Home Edition. For TEOAEs measurement, click stimulus with amplitude of 80 dB SPL and duration of 80 μ s was used. TEOAEs were recorded at the frequencies of 1.0, 1.4, 2.0, 2.8, and 4.0 kHz. According to the manufacturer's instructions, for the frequency of 1000 Hz, a sound-to-noise ratio (SNR) value (representing the difference between OAE amplitude and noise floor), ≥ 3 dB SPL was considered as present TEOAEs. For the rest of the tested frequencies (1400, 2000, 2800, and 4000 Hz), 6dB SPL was considered as the minimum value indicating presence of TEOAEs. DPOAEs were obtained with primary tone level of L1 and L2 as 65 and 55 dB SPL, respectively, and frequency ratio f_2/f_1 as 1.22. DPOAEs amplitudes were recorded and plotted as DP gram at 1.0, 1.4, 2.0, 2.8, and 4.0 kHz. The criteria for their presence were the same with those for TEOAEs.

Surgical procedures

Informed consent was obtained from all participants. The patients were operated on under general anesthesia by 2 experienced surgeons. According to the surgeon's preference, small fenestra stapedotomy was performed in 27 cases and a microtraumatic modification of the procedure [11] was performed in 24 individuals.

During small fenestra stapedotomy, an endaural incision was made. The chorda tympani nerve was identified and gently preserved and the ossicles' fixation was confirmed. The incudostapedial joint was separated, the stapes tendon was cut with microscissors, and the stapes superstructure was removed after the fracture of the stapes crura. Creation of a small fenestra stapedotomy was succeeded by using a burr slightly larger than the intended prosthesis. A titanium prosthesis of 0.5 mm in diameter and 4.5 mm long was inserted and the oval window was sealed with small pieces of connective tissue, filling the oval window niche.

In the variant of microtraumatic stapedotomy [11], after separating the incudostapedial joint, a fissure was opened in the center of the union of the middle and posterior third of the footplate. Following the fracture of the stapes crura, the stapes superstructure with the stapes tendon intact was left lying or bending on the promontory. A Schuknecht prosthesis 4.5 mm long was inserted and the oval window was sealed with small pieces of connective tissue, filling the oval window niche and the area between the stapes crura and covering the piston's whole length.

Statistical analysis

Data analysis was performed by means of SPSS software (release 19.0) (SPSS Inc, Chicago, Illinois). Laboratory data between the two surgical groups were correlated by using the Mann-Whitney U test. The postoperative outcomes of the applied procedures were estimated by using the paired Wilcoxon test. Any p-value less than 0.05 was considered statistically significant.

Results

Preoperative findings

The outer ear canal and tympanic membrane was found normal in all patients suffering from otosclerosis. The stapedial reflex was absent in all cases. Type A tympanogram was recorded in 9 cases and type As tympanogram was evident in the remaining 42 cases.

Overall, the mean air hearing threshold of the 51 patients included in the study was 55.7 ± 10.6 dB, the mean bone hearing threshold was 32.1 ± 10.2 dB, and the mean air-bone gap, calculated for the speech frequency range between 500 and 4000 Hz, was 23.8 ± 6.1 dB. The mean resonant frequency value, derived by multifrequency tympanometry testing, was 1268.63 ± 188.4 Hz. The comparison of patients' auditory responses preoperatively revealed no statistically significant differences between the 2 surgical groups (Table 1).

Table 1. Preoperative patients' auditory data of the otosclerotic ears in accordance to the planned surgical procedure.

Preoperative auditory responses	Small fenestra stapedotomy	Microtraumatic stapedotomy	p
Air hearing threshold (mean ±SD), dB	54.8±11.2	56.6±9.9	0.557
Bone hearing threshold (mean ±SD), dB	32.2±11.4	31.8±8.9	0.889
Air-bone gap (mean ±SD), dB	22.9±5.2	24.8±6.6	0.260
Resonant frequency (mean ±SD), Hz	1292.6±191.1	1241.7±185.7	0.340

Table 2. Preoperative OAEs detection at the tested frequencies, according to the planned surgical intervention. No statistically significant differences were evident between the two surgical groups at all frequencies.

Frequencies examined	Type of OAEs	Small fenestra stapedotomy (No. of patients)	Microtraumatic stapedotomy (No. of patients)	Total (No. of patients)	P
1 kHz	TEOAEs	6	2	8	0.621
	DPOAEs	0	1	1	0.933
1.4 kHz	TEOAEs	0	2	2	0.130
	DPOAEs	1	0	1	0.933
2 kHz	TEOAEs	0	0	0	–
	DPOAEs	0	0	0	–
2.8 kHz	TEOAEs	0	0	0	–
	DPOAEs	1	0	1	0.933
4 kHz	TEOAEs	0	0	0	–
	DPOAEs	0	1	1	0.933

The detection of TEOAEs and DPOAEs was tested in 5 frequency steps: 1, 1.4, 2, 2.8, and 4 kHz. The first 2 steps (1 and 1.4 kHz) were considered as low-level frequencies and the others (2, 2.8, and 4 kHz) were considered as high-level frequencies.

Preoperatively, totally absent TEOAEs were found in 41 patients (80.4%). Amplitudes significantly exceeding the background noise level were detected in 10 patients (19.6%), all at low frequencies (8 cases at 1 kHz and 2 cases at 1.4 kHz). There were no patients with present TEOAEs at high frequencies. Concomitantly, 47 patients (92.2%) exhibited total absence of DPOAEs, preoperatively. Four patients (7.8%) presented amplitudes significantly exceeding the background noise level. Two cases involved detection at low frequencies (1 and 1.4 kHz) and 2 cases at high frequencies (2.8 and 4 kHz).

When the preoperative status of the detection of OAEs was stratified according to the planned surgical intervention, no statistically significant differences were recorded between the 2 groups of patients, in both TEOAEs and DPOAEs testing (p 0.621 and p 0.903, respectively). Furthermore, no statistically

significant differences in OAEs' detection between the 2 surgical groups were noted when the testing was stratified by the frequencies examined (Table 2).

The mean air and bone hearing thresholds in the control group were calculated at 7.6±4.3 dB and 5.7±3.9 dB, respectively. The mean air-bone gap measurement was 1.87±1.8 dB. TEOAEs and DPOAEs were present in all subjects and in all frequencies examined. Multifrequency tympanometry testing was also applied in all normal hearing subjects and resonant frequency was calculated at 923±125.1 Hz.

Postoperative findings

The mean hospital stay of the patients was 2.1±0.2 days. No statistically significant differences were recorded among the 2 surgical groups (p=0.251). There were no perioperative complications.

Follow-up was eligible for all cases (100%). All patients described improved hearing in the operated ear. Independently

Table 3. Postoperative comparative auditory data of the patients' operated ears in the two surgical groups.

Post-operative auditory responses	Follow-up intervals	Small fenestra stapedotomy	Microtraumatic stapedotomy	p
Air hearing threshold (mean ±SD), dB	2 nd month	35.32±9.4	33.33±7.8	0.683
	5 th month	33.10±10.1	30.62±7.2	0.293
Bone hearing threshold (mean ±SD), dB	2 nd month	25.55±10.7	23.17±6.9	0.091
	5 th month	24.57±10.8	22.56±10.6	0.221
Air-bone gap (mean ±SD), dB	2 nd month	9.90±4.4	10.15±4.8	0.955
	5 th month	7.54±3.9	8.07±4.8	0.192
Resonant frequency (mean ±SD), Hz	2 nd month	–	–	–
	5 th month	230.37±56.5	791.60±126.01	<0.001

of the type of the procedure, the overall mean air and bone hearing threshold and mean air-bone gap, which were calculated at 2 and 5 months postoperatively, were improved significantly compared to the preoperative values ($p < 0.001$). The stratification of postoperative data according to the type of the procedure confirmed the improvement of the auditory responses in both surgical groups; however, no statistically significant differences in the postoperative outcome were evident (Table 3).

Postoperative resonant frequency data (RF) were derived only in the 5th postoperative month in order to avoid any possible complications associated with the testing in an earlier postoperative period. Mean measured value was 570.52 ± 152.9 Hz, exhibiting a statistically significant reduction compared to the preoperative measurement of 1268.63 ± 188.4 Hz ($p < 0.0001$). However, the assessment of resonant frequency data in the 2 surgical groups indicated that RF was almost normalized in the microtraumatic stapedotomy group (791.60 ± 126.01 Hz). In contrast, the patients who underwent the small fenestra technique exhibited an enormous decrease in RF value postoperatively (230.37 ± 56.5 Hz) ($p < 0.001$, Table 2).

OAEs testing at follow-up intervals indicated statistically significant improvement in the detection of all OAEs. However, when the postoperative detection was stratified by the tested frequencies, statistically significant increase in the number of patients with present TEOAEs and DPOAEs was seen only at 1 and 1.4 kHz (low frequencies) ($p < 0.001$). Statistically significant improvement in the detection of OAEs in high frequencies was recorded only during the follow-up on the 5th postoperative month and involved only the detection of DPOAEs ($p < 0.05$). The above findings were constant after both small fenestra and microtraumatic stapedotomy, except for some minor differences involving the presence of DPOAEs at high frequencies (Figures 1 and 2). Moreover, correlation analysis failed to exhibit any significant association between the type of the procedure and postoperative OAEs responses ($p = 0.896$,

0.714 for TEOAEs testing and $p = 0.366, 0.320$ for DPOAEs testing at 2 and 5 months after surgery, respectively).

Regression analysis was performed to verify whether any given middle ear resonant frequency in the 5th postoperative month could affect the response levels found at certain frequencies in OAEs testing. Regression modeling failed to verify any association between TEOAEs' and DPOAEs' best frequency responses with middle ear's resonant frequency in both surgical groups. None of the models presented satisfactory adjustment levels to confirm the hypothesis that emissions could be affected directly by middle ear resonance features.

Discussion

The current study examined the effect of 2 types of stapes surgery in the profile of otoacoustic emissions in patients with otosclerosis. The results were associated with the middle ear's resonant frequency, which was derived by multifrequency tympanometry. Our results indicate that the detection of OAEs is significantly improved after both small fenestra and microtraumatic stapedotomy and especially during testing at low frequencies. Nevertheless, only the ears operated on with the microtraumatic technique presented resonant frequency values within the normal range, postoperatively. This was reflected in better hearing quality and less loud-noise intolerance reported by this group of patients.

According to the literature, in normal middle ear conditions, TEOAEs and DPOAEs are measurable at all frequencies in individuals with hearing threshold better than 30 and 55 dB, respectively [6]. This is validated by the auditory results of the normal-hearing subjects included in our study. In otosclerosis, the sound transmission towards the inner ear is affected and subsequently leads to a conductive hearing loss. Since otosclerotic abnormalities also affect the antidromic sound transmission from the inner through the middle ear into the outer ear

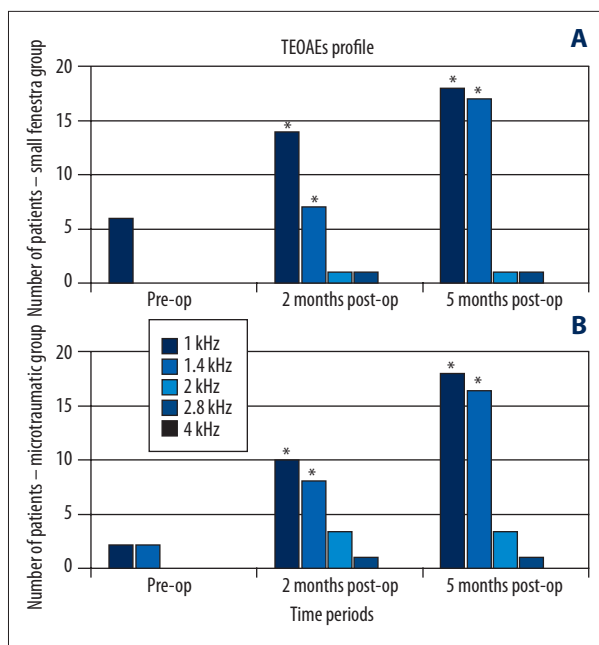


Figure 1. TEOAEs responses in otosclerotic patients undergoing: (A) small fenestra and (B) microtraumatic stapedotomy. In both surgical groups, statistically significant postoperative increase was recorded in the number of patients with detectable TEOAEs only at 1 and 1.4 kHz (low frequencies) (* $p < 0.05$)

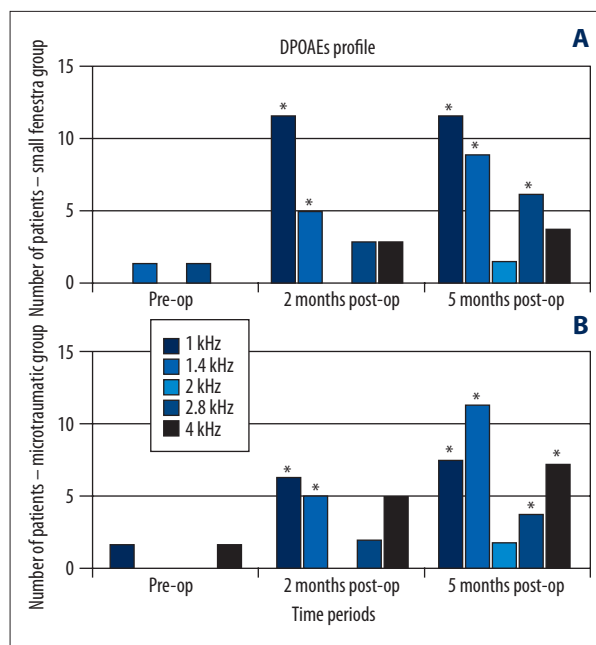


Figure 2. DPOAEs responses in otosclerotic patients undergoing: (A) small fenestra and (B) microtraumatic stapedotomy. In both surgical groups, statistically significant postoperative increases were recorded in the number of patients with detectable DPOAEs at 1 and 1.4 kHz. At higher frequencies, statistical significance was achieved only in the 5th postoperative month – at 2.8 kHz in the small fenestra group and at 2.8 and 4 kHz in the microtraumatic group (* $p < 0.05$).

canal, these ears present with absent or markedly reduced OAEs detection [12]. In the current study, hearing thresholds explain the absence of OAEs in most of the cases, preoperatively. However, although postoperative mean hearing thresholds were within range where OAEs were likely detectable, both TEOAEs and DPOAEs were not steadily detected. The results of the current study are consistent to the literature data indicating that OAEs are not always detected in cases of middle ear dysfunction history, despite the presence of normal audiometry measurements [13]. Thus, OAEs probably represent a more sensitive testing, reflecting the alterations of conduction in the middle ear compared to traditional audiometry.

Reports on the effect of stapes surgery on evoked OAEs are limited in the reviewed literature and have shown varying results. Transient evoked OAEs are usually detected in only a small number of patients after stapes surgery [14], while DPOAEs are more frequently reported after successful stapedectomy [15]. After stapes surgery, the mobility of the ossicular chain is restored, so TEOAEs and DPOAEs should be detectable within their measurable range (30 or 55 dB HL, respectively).

In general, OAEs are absent in most patients with otosclerosis [16,17]; however, preoperative TEOAEs and DPOAEs were present in 19.6% and 7.8% of our patients, respectively. The

detection of OAEs was evident mostly at low frequencies (1 and 1.4 kHz) preoperatively, while significant improvement was noted after surgery, especially at this frequency range. The improvement of OAEs' detection was more evident in the patients who underwent microtraumatic stapedotomy, although no statistically significant difference was recorded.

The reasons remain somewhat unclear why OAEs are recorded mostly at low frequencies in most patients after both types of stapes surgery, although the individual's air bone gap is sufficiently closed. A hypothetical explanation of this phenomenon could be elicited by 3 conditions [15]: 1) an increase in the mass, 2) an increase in the stiffness, and 3) a clinically unapparent perilymph leak. Data supporting any crucial role of mass increase of the middle ear transmitting structures are lacking. On the other hand, the increase of stiffness in these structures appears to be the most important reason for OAEs' measurement only in a narrow frequency range, postoperatively. This may be attributed to scar formation around the inserted piston in the oval window niche and/or the clamping of the prosthesis loop around the long process of the incus [18]. The third factor could be a functionally incomplete coupling of the piston within the vestibule. However, all the above conditions can impede the reverse transmission of OAEs.

Multifrequency tympanometry has gained popularity over the last 3 decades compared to standard low-frequency technique. The latter fails to reveal a distinct pattern for many middle ear diseases, including otosclerosis; this is mainly due to the status of the tympanic membrane, which dominates the tympanogram and thus effectively overshadows conditions affecting more medial structures [19].

Since the original Margolis and Goycoolea study [20], which gained remarkable popularity, many recent studies have suggested that the identification of otosclerosis can be substantially improved using measures derived from multifrequency tympanometry or by combining tympanometric variables in specific ways [21]. The estimated mean resonant frequency values in our study in normal subjects and otosclerotic patients before any surgical intervention are also in accordance with the available literature data [22]. Stapes surgery resulted in a significant reduction of the mean resonant frequency value in our series. However, the resonant frequency was enormously decreased in the patients undergoing small fenestra stapedotomy, explaining the complaints of fullness and discomfort that these patients described postoperatively. This may be attributed to the non-physiological condition of superflaccidity observed in these operated ears, similar to ossicular chain discontinuity. In contrast, the ears operated on with the microtraumatic technique [11] showed a resonant frequency within the normal range. This was reflected in better hearing quality and less loud-noise intolerance reported by this group of patients. This is the main advantage of the microtraumatic technique compared to the small fenestra stapedotomy.

Conflicting results have been reported concerning any possible association of TEOAEs and DPOAEs testing with middle ear

resonant frequency, which was also a goal of our study. Most studies report that there is a concentration of higher TEOAEs response levels at middle frequencies, and of DPOAEs at higher frequencies; however, no significant influence of middle ear resonant frequencies on the response level at specific TEOAEs and DPOAEs frequencies has been reported [23]. The results of our study suggest that the response levels of otoacoustic emissions are not predominantly affected by the primary middle ear resonance, failing to verify any association between TEOAEs' and DPOAEs' responses with middle ear's resonant frequency. This finding was consistent in both types of procedures examined.

These results show that resonances are only a small element among the complex factors involved in simultaneous forward and reverse transmission of stimuli and responses. Certain elements probably contribute by providing important information about the effect of otosclerosis and stapes surgery on OAEs, as well as about auditory system integration. Although OAEs cannot replace behavioral threshold tests, they should be considered as a useful and sensitive adjunct to the other tests available for complete clinical follow-up and efficient monitoring after stapes surgery [24].

Conclusions

Despite hearing improvement and sufficient air-bone gap closing, OAEs are not steadily detected following either small fenestra or microtraumatic stapedotomy. Resonant frequency is significantly improved after the microtraumatic technique, representing a useful adjunct to conventional pure tone audiometry for the evaluation of the surgical outcome in otosclerotic patients undergoing stapes surgery.

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