

Analysis of the Mechanical-Acoustic Features of the Middle Ear After Stapedial Surgery Both With and Without Stapes Muscle Preservation

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Introduction and objective: Stapes replacement surgery performed in cases of otosclerosis alters various anatomical (ossicular, ligament, and tendon) elements of the middle ear affecting their physical properties. The goal of our work is to determine which of the surgical techniques applied during otosclerosis most respects the mechanical-acoustic features of the middle ear.

Patients and method: We analyzed the audiological and admittance results of 100 patients who underwent various stapedial replacement techniques and compared them to 20 otologically healthy subjects.

Results: The audiological results obtained are similar in the different surgical techniques compared. However, those techniques in which the stapedial muscle tendon is preserved offer similar hearing resonance frequencies post intervention as healthy ears, which was not found to be the case in the remaining techniques evaluated.

Conclusions: We feel that the stapedial tendon should be preserved during otosclerosis surgery as the mechanical-acoustic features of the ear are thus better conserved, leading to enhanced language recognition in noisy environments.

Key words: Stapedial surgery. Multifrequency tympanometry. Otosclerosis. Resonance frequency.

Estudio de las características mecanoacústicas del oído medio sometido a cirugía estapedial con y sin conservación del tendón del estribo

Introducción y objetivos: La cirugía de sustitución estapedial realizada en casos de otosclerosis altera diversos elementos anatómicos del oído medio (osiculares, ligamentosos y tendinosos), lo que modifica sus propiedades físicas. El objetivo del trabajo es determinar qué técnicas de las practicadas durante la cirugía de la otosclerosis respetan más las características mecanoacústicas del oído medio.

Pacientes y método: Estudiamos los resultados audiológicos y admitanciométricos de 100 pacientes sometidos a diversas técnicas de sustitución estapedial y los comparamos con los de 20 sujetos otológicamente sanos.

Resultados: Los resultados audiológicos obtenidos son similares en los diversos tipos de técnicas quirúrgicas comparadas; sin embargo, las que respetan el tendón del músculo estapedial presentan, tras la intervención, frecuencias de resonancia del oído similares a los oídos sanos, lo que no ocurre con las demás técnicas evaluadas.

Conclusiones: A la luz de los resultados, consideramos que debe conservarse el tendón estapedial durante la cirugía de la otosclerosis, ya que de este modo se preservan mejor las características mecanoacústicas del oído, lo que repercute en una mejor discriminación del lenguaje en ambientes ruidosos.

Palabras clave: Cirugía estapedial. Timpanometría multifrecuencia. Otosclerosis. Frecuencia de resonancia.

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INTRODUCTION

Two of the most widespread techniques for the treatment of otosclerosis are stapedectomy and stapedotomy, in which the footplate is approached systematically by sectioning the stapedius tendon. The modifications introduced to techniques with the purpose of preserving the stapedial muscle tendon have had less acceptance, despite being more compatible with the anatomy of the middle ear.

Over the years, dozens of papers have been dedicated to comparing the audiological results obtained with different techniques of stapedial substitution, none of which have been demonstrated to be better than others in terms of improvement of the auditory thresholds referred to,^{1,2} even though some authors defend stapedotomy with calibrated platinotomy and insertion of a venous graft as the best stapedial substitution technique.³⁻⁵ We thus consider the debate closed in audiological terms. But other questions still remain on this type of surgery: Does the stapedial muscle section lack functional importance? Is the damage inflicted on the ossicular, tendinous and ligamentous structures during otosclerosis surgery free of mechanical-acoustic repercussions? The study undertaken here is intended to provide answers to these questions since, even though in the short term the published results seem to be similar in the different techniques used, it is necessary to know the effect of each one on the mechanical and acoustic, not just audiological, characteristics of the middle ear.

In the middle ear, as it is a mechanical system, the acoustic characteristics are modified in line with changes in rigidity, friction, and the mass of the elements that compose it.^{6,7} In this sense, any surgical procedure that alters 1 or more of these parameters is reflected in the mechanical-acoustic characteristics of the middle ear.⁸⁻¹³ In carrying out a classic stapedial substitution as a treatment for otosclerosis, we not only eliminate an ossicular element; we also reduce the rigidity of the system by eliminating the annular ligament and sectioning the stapedial muscle tendon (this reduction in rigidity may be even greater if the posterior tympanomalleal ligament is disinserted during the surgical approach).

The diminishment of the rigidity in this mechanical system results in the resonance frequency being displaced towards lower frequencies, as reflected in the equation determining impedance in a mechanical system (Figure 1). This consideration is especially important in the ear since, if we displace the resonance frequency towards lower frequencies (a fundamental component of sound), the transmission of the latter is facilitated by the middle ear to the detriment of higher frequencies, implying a worsening of word discrimination in noisy environments.^{14,15}

Various techniques have been described for the surgical treatment of otosclerosis in order to preserve the stapedial muscle tendon. In all these, the preservation of the stapedius tendon implies an important biological improvement with respect to sectioning techniques since, on the one hand they maintain a cochlear protection system in the face of intense noises and on the other they preserve the vascularization that, from the tendon, reaches the long apophysis of the incus (thus preventing its necrosis by ischaemia), but we don't know the mechanical-acoustic consequences of either maintaining the union of the ossicular chain to the stapedial muscle or eliminating this connection. In the present paper, we explore the mechanical-acoustic consequences in the middle ear of maintaining the stapedial tendon muscle, which can be of 2 types: static (due to increased rigidity of the system when the tendon is preserved) and dynamic (by the contraction of the stapedial muscle, displacing the

$$Z = \sqrt{R^2 + (2 \pi f M - \frac{1}{2 \pi f r})^2}$$

Figure 1. Equation determining impedance in a mechanical system. This impedance depends on friction (dissipative component) and on rigidity and mass (both non-dissipative components). The influence of mass in impedance is directly proportional to the frequency, whereas the influence of friction is inversely proportional to the frequency studied.
f indicates frequency; M, mass; R, friction; r, rigidity.

resonance frequency of the middle ear towards higher-pitched tones, impeding the passage of sound and consequently improving word discrimination in a noisy environment).

The objective of the present work is to determine the mechanical-acoustic characteristics present in the human middle ear subjected to different stapedial surgery techniques, comparing the values obtained with the same parameters in adult subjects with non-pathological ears.

PATIENTS AND METHOD

To achieve the goals set in this work we have analyzed the audiological and mechanical-acoustic results of 100 ears corresponding to 91 patients on whom, following a diagnosis of otosclerosis, some type of stapedial surgery had been performed (subtotal platinectomy, posterior hemiplatinectomy, stapedectomy, and stapedotomy without conservation of the stapedius tendon muscle, and all those same techniques with conservation). All the cases were operated on sequentially between 2003 and 2004.

We have collected and analyzed the data of 20 otologically healthy subjects that have served as a control group. The data obtained from the 100 ears operated on were grouped into 3 categories according to the surgical technique performed. We thus obtained four groups:

Group A: 20 otologically healthy adult patients (11 women and 9 men). All them were fourth-year medical students who voluntarily agreed to participate in the study. The average age was 22 years. The data obtained were used to determine the resonance frequency in the ears of otologically healthy subjects.

Group B: 51 ears (corresponding to 47 patients) on which a stapedectomy was performed by sectioning the stapedial tendon and inserting a vein or perichondrium. In 7 cases the platinectomy was incomplete because of anatomical difficulties (partial posterior platinectomies, called posterior hemiplatinectomies in Table 1). Of this group, 41 patients were women and 10 men. The mean age was 42 years.

Group C: 24 ears (corresponding to 21 patients) on whom a stapedectomy was performed with preservation of the stapedial tendon and insertion of a vein. In 3 of them a calibrated platinotomy was performed (shown in Table 1 as a stapedotomy conserving the tendon); 4 of them were men and 20 women. The mean age was 43 years.

Post-Surgical Differential Hearing Threshold

	Ears, n	Mean Differential Prior to Surgery	Mean Differential After Surgery	Bone Route After (Surgery (Better), n	Bone Route After Surgery (Worse), n	<10 dB	10-20 dB	>20 dB
Stapedectomy with preservation of the stapedial tendon	21	36	10	13	8	11	8	2
Stapedectomy without preserving the tendon	44	38	6	35	9	15	26	3
Stapedectomy	25	39	12	10	15	9	12	4
Partial platinectomy	3	37	8	1	2	1	1	1
Posterior hemiplatinectomy	4	39	6	3	1	3	1	0
Stapedotomy with preservation of stapedial tendon	3	41	5	1	2	3	0	0

Group D: 25 ears (corresponding to 20 patients) on whom a stapedotomy was performed without the insertion of any graft and without conserving the stapedial tendon. There were 24 women and 1 man. The mean age was 39 years. The criteria for including the patients in the study were: confirmed clinical otosclerosis and subsequent surgery; no previous otological condition (exposure to work noise, the taking of ototoxic drugs, or ear infections); absence of endolabyrinthine vertigo, and the presence of non-pathological external auditory canals.

The prostheses utilized during the stapedial substitution were platinum-teflon (0.6 mm wide) in 75 cases and fluoroplastic (4 mm wide) in the rest. The length varied between 4.5 and 5.5 mm.

Otoscopy, tonal audiometry, and a study of multifrequency admittance were performed on the group of volunteers. An otomicroscopy, tonal liminar audiometry, and admittance testing were performed on the patients in the study prior to surgery. At 1 month and at 3 months after surgery, we carried out a new admittance study to determine the resonance frequency of the ear operated on, as well as the admittance components (susceptance and conductance). The pre- and post-surgery audiometric values were evaluated according to the criteria of the American Academy of Otolaryngology-Head and Neck Surgery,¹⁶ except with regard to the 3 kHz thresholds, which were replaced by the 4 kHz threshold. The audiometry check-up was performed 6 months after surgery.

To compare whether the audiological results (mean post-surgery differential hearing threshold [DHT] and difference between the bone thresholds before and after surgery) observed between the different techniques of stapedial substitution showed statistically significant differences or were due to chance, we used the Kruskal-Wallis as a hypothesis contrast test (comparison of various independent sample averages which are not shown to follow a normal distribution). The significance level chosen is 1% ($P < .01$). To analyze the numerical data, we used the SPSS statistical programme in its version 6.0.1.

A resonance frequency analysis was performed on all the patients, as well as the parameters determining impedance in the human middle ear (susceptance and conductance determined by mass, rigidity and friction) (Figure 1) utilizing an Ampliad-728 multifrequency admittance meter, for which we used 4 base tones: 226, 678, 800, and 1000 Hz.

The present study has been carried out following the international ethical recommendations on clinical research.

RESULTS

Audiological Results (Table 1)

Group A. All the volunteers studied presented normal hearing (considering as such an average loss <20 dB in the range of frequencies 250-8000 Hz).

Group B. The mean hearing loss before surgery in this group was 38 dB HL and post-surgery it was 8 dB HL. The post-surgery DHT was found in the majority of the patients (56.8%) at 10-20 dB, but primarily in levels close to 10 dB. In 4 cases (7.8%), post-surgery DHT was >20 dB. In 18 patients (35.3%) there was a complete closing of DHT. Bone conduction worsened in 13 (25.5%) of the cases operated on with this technique, and stayed the same or improved in 38 (74.5%).

Group C. The mean hearing loss before surgery in this group was 37 dB HL and post-surgery, 9 dB HL. The post-surgery DHT was found in the majority of the patients (58.4%) to be below 10 dB. In 2 cases (8.33%) the post-surgery DHT was >20 dB, after performing a total platinectomy in both. In 8 patients (33.33%) there was an incomplete closing (10-20 dB) of the differential hearing threshold. Bone conduction worsened in 10 (41.6%) of the cases operated on with this technique and stayed the same or improved in 14 (58.4%).

Group D. The mean hearing loss before surgery in this group was 39 dB HL and post-surgery, 12 dB HL. The post-surgery DHT was found in 48% of patients in this group to be between 10 and 20 dB. In 4 cases (16%), post-surgery DHT was >20 dB and 9 patients (36%) presented a differential hearing threshold with a separation <10 dB after the surgery with this technique. Bone conduction worsened in 15 cases

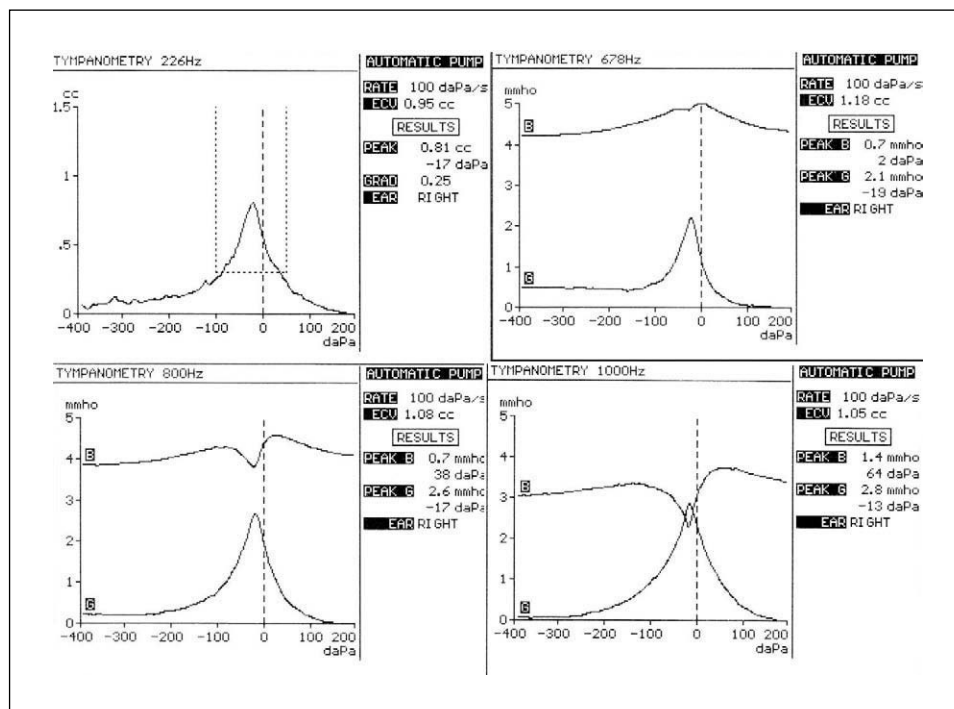


Figure 2. Admittance graphs (with the 4 tones utilized in the study) of 1 of the controls whose resonance frequency was found to be close to 800 Hz.

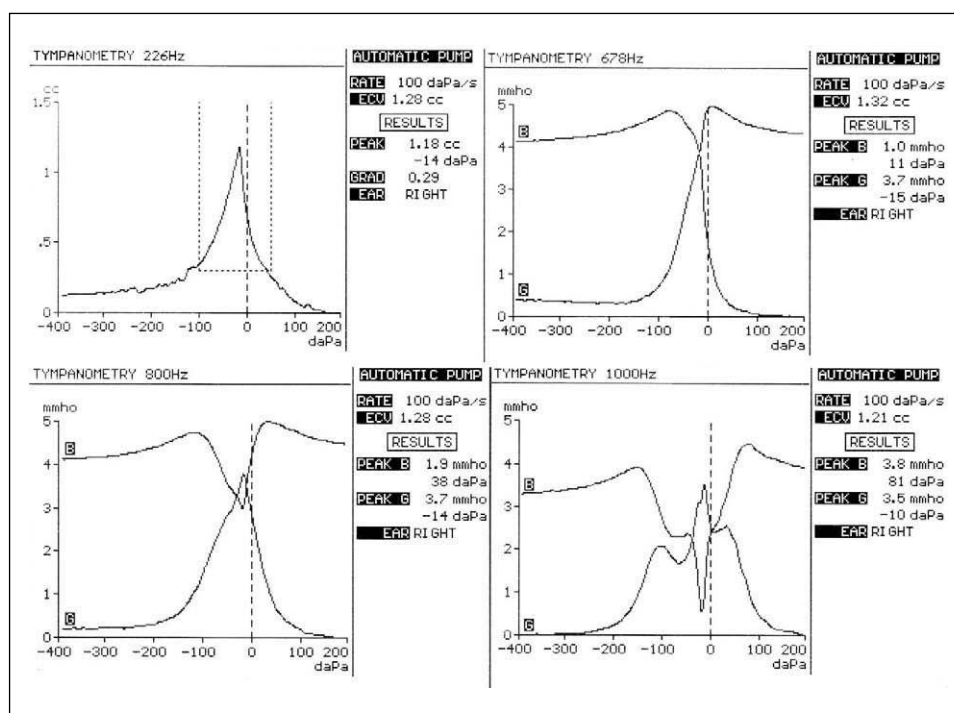


Figure 3. Admittance study in 1 of the patients operated on with a stapedectomy without conservation of the tendon and with insertion of a venous graft, in which the resonance frequency after the intervention was found to be close to 678 Hz one month following the operation.

(60%) operated on with this technique and stayed the same or improved in 10 (40%).

The audiological results in the 3 groups of patients operated on did not show statistically significant differences in the check-up carried out 6 months after the operation, which we compared by pairs (post-surgery average DHT, $P=.645$; difference between the pre-surgery and post-surgery bone conduction thresholds, $P=.082$).

Mechanical-Acoustic Results

Group A. In 14 men and 2 women the resonance frequency was found between 800 and 1000Hz, Figure 2). Two men presented resonance frequencies between 678 and 800 Hz; one <678 Hz and another >1000 Hz. The resonance frequencies in these healthy volunteers were similar, in the range of 2 resonance frequencies, in both ears in all the volunteers studied.

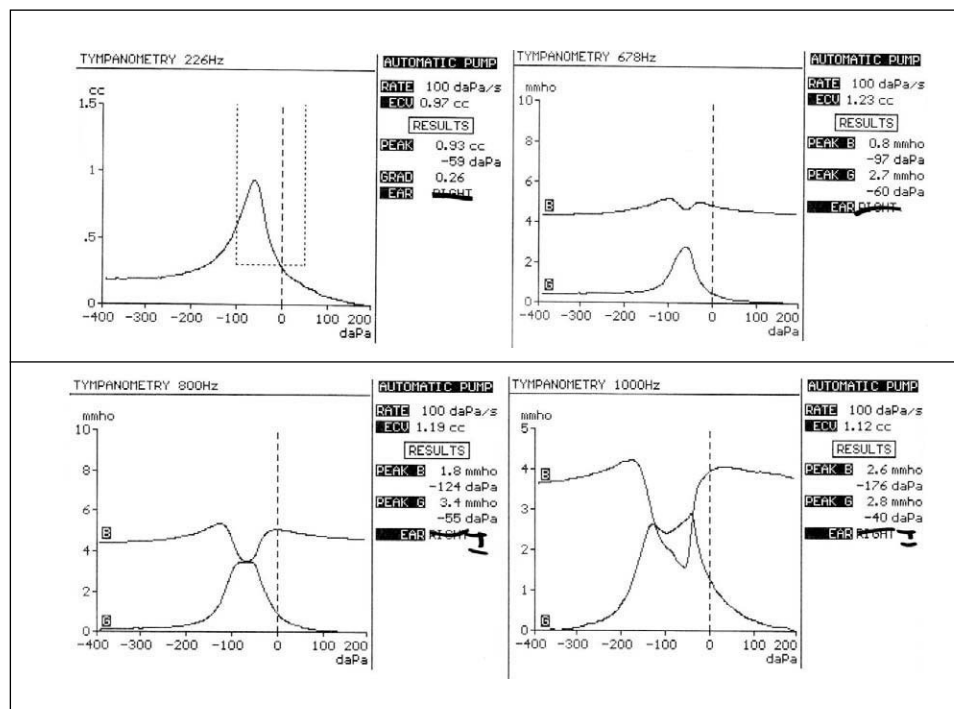


Figure 4. Admittance study of 1 of the patients operated on by stapedectomy without preservation of the tendon and with insertion of a venous graft, in which the resonance frequency after the operation was found to be above 678 Hz 3 months after surgery.

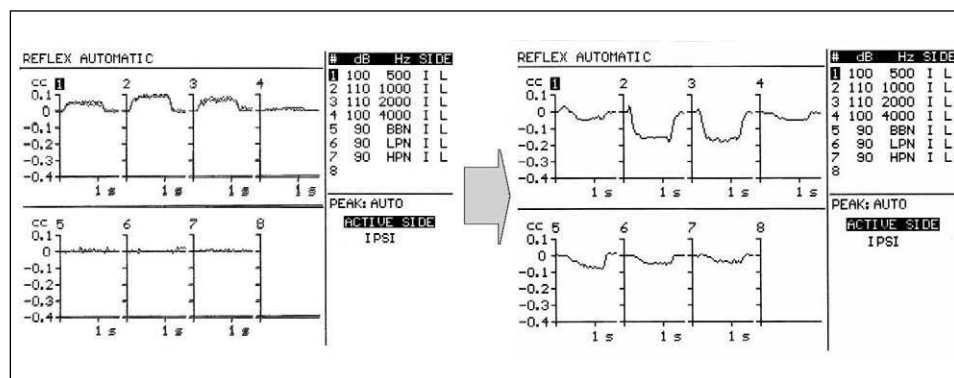


Figure 5. An inverted acoustic effect is observed in the left graph in an otosclerotic patient (on which the graph obtained during muscular relaxation of the patient is practically superimposed). The right graph shows normal stapedial reflex in the same patient following a stapedectomy operation with preservation of the stapedial tendon.

Group B. The ears of the patients on whom a classic stapedectomy was performed without conserving the stapedial tendon but inserting a venous graft or perichondrium presented resonance frequencies of >1 kHz in the ear affected by otosclerosis in all cases except for 3:2 with resonance frequency between 0.8 and 1 kHz and $1 < 676$ Hz. In all of them, the lack of mobility of the stirrup was checked intraoperatively. Even though it was not systematically looked for in all the cases operated on, in those in which it was sought, an inverted ipsilateral acoustic effect was found in the pathological ear. After surgery, the mean resonance frequency of this group descended below 678 Hz in the follow-up 1 month after surgery (Figure 3) and was mainly (78.43%) between 678 and 800 Hz 3 months after surgery (Figure 4). The morphology of the susceptance and conductance curves appears wider than in the control subjects, and frequently, in the case of conductance, have a "double hump" or inverted "W" morphology.

Group C. The pre-surgery resonance frequency in the 24 ears with otosclerosis operated on with preservation of the

stapedial tendon was >1 kHz in 22 cases and between 0.8 and 1 kHz in the other 2. In all the cases studied an inverted acoustic effect was found in at least 2 of the frequencies tested (500 and 1000) which occasionally appeared at 2000 Hz. In 1 of the cases in which the inverted effect appeared, we noticed that this persisted even during the intraoperative anaesthetic relaxation and disappeared a month after operation, at which time an acoustic reflex of normal characteristics was present (Figure 5). After the surgical treatment, in the first follow-up visit, the resonance frequency fell and was mainly found (83.3%) to be below 678 Hz. Moreover, the morphology of the conductance and susceptance curves appeared altered, with anomalous graphs, showing more frequent peaks and troughs the closer the result was to the extreme negative values of the pressure pump (central graph in Figure 6). These anomalous graphs disappeared in all cases 3 months after the operation. At that time the average resonance frequency of this group was between 0.8 and 1 kHz (right graph Figure 6). We detected a stapedial reflex (typical negative deflection in response to

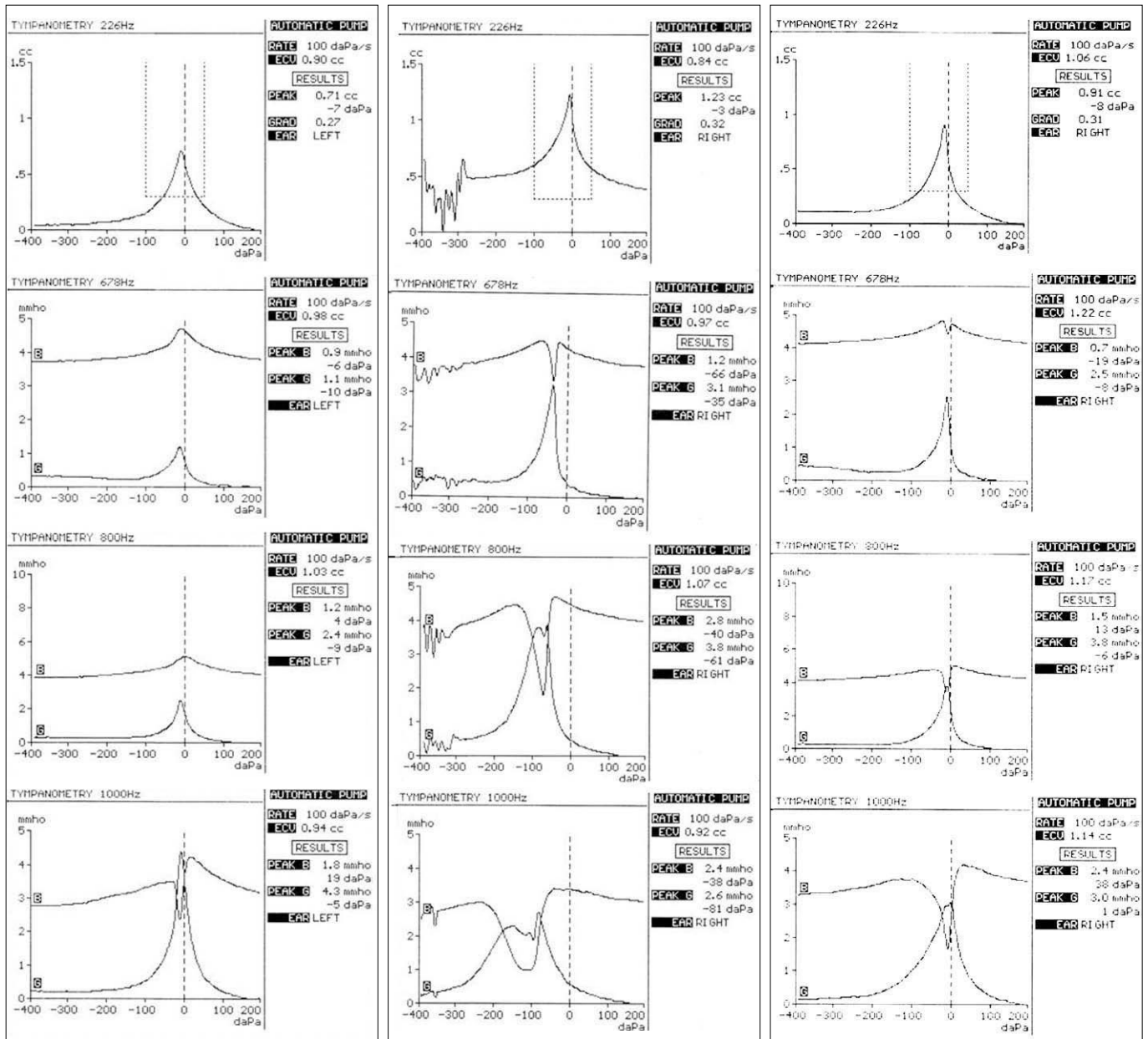


Figure 6. The graphs situated to the left show the admittance testing curves of a patient afflicted with otosclerosis; it can be seen that the resonance frequency is above 1 kHz. The central graphs show the admittance curves one month after the procedure with preservation of the tendon. The right graphs in the Figure show the admittance curves at 3 months.

a sound above 80 dB) in only 5 (20.8%) of the patients of this group 1 month after the operation. Six months after the operation this was present in 41.6% of the patients with whom the stapedial muscle tendon was preserved during surgery.

Group D. The pre-surgery resonance frequency of the 25 ears subsequently operated for otosclerosis with performance of platinotomy was >1 kHz in 22 cases and 0.8-1 kHz in the other 3. In the first follow-up visit after surgery, the resonance frequency was lower and was found in all cases to be below 678 Hz. Moreover, the morphology of the conductance and susceptance curves is extremely altered, with anomalous graphs and images of double or triple "humps" (Figure 7).

These anomalous graphs were maintained in all cases 6 months after the procedure. At that time the average resonance frequency in this group was below 678 Hz in 80% of the cases (Figure 8).

DISCUSSION

The most peripheral portion of the human ear behaves, and should thus be considered, as a mechanical system composed of ossicular, tendinous, membranous, and muscular elements; these last are the cause of the non-linear behaviour of the middle ear above certain sound intensities.

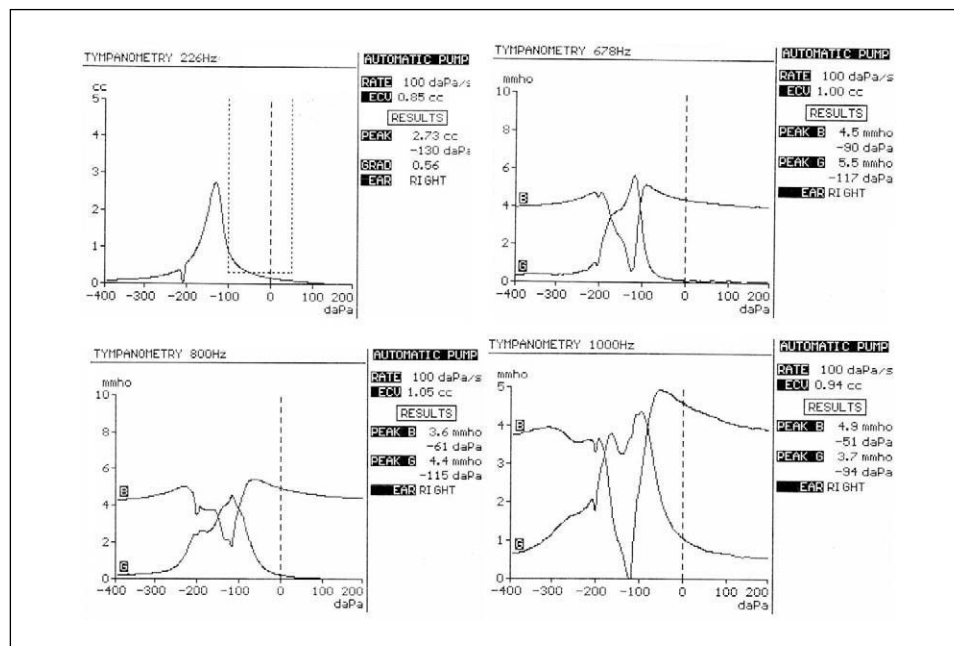


Figure 7. First admittance metering follow-up for a patient subjected to a stapedotomy without graft insertion. The resonance frequency is displaced to low-pitch frequencies (<678 Hz).

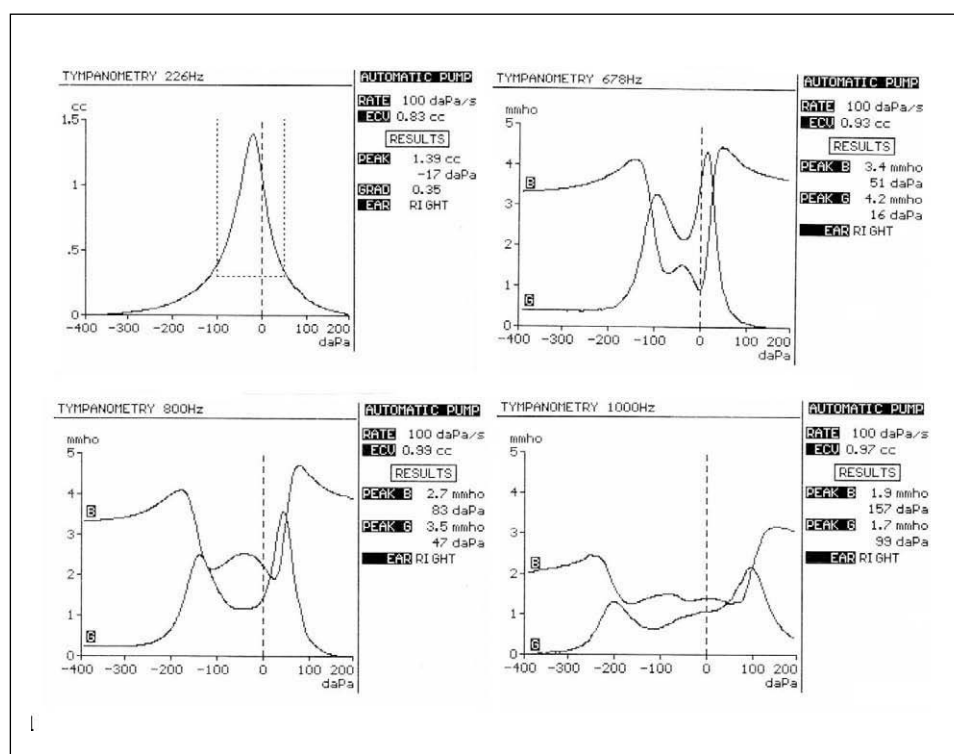


Figure 8. Admittance metering follow-up for a patient subjected to a stapedotomy without graft insertion 6 months after the procedure. The resonance frequency remains displaced towards low-pitch frequencies (<678 Hz).

As a mechanical system, the mechanical-acoustic behaviour of the ear is subject to the same laws that govern such physical systems. Some of the characteristics of a physical system are impedance (difficulty that an environment poses to the deformation or passage of energy) and its inverse, immittance (in this case it would be the facilitation of a mechanical system to the deformation or passage of energy). The impedance (Z) of the external and middle portions of the human ear is determined by the mass of the elements comprised, as well

as by its rigidity and the friction between them, and the contribution of each one to the total admittance value is determined by the equation in Figure 1. The admittance (Y) would be its inverse ($1/Z$). Friction results in a loss of energy, and thus is known as a dissipative component of impedance, while mass and rigidity, even though they pose an obstacle for the passage of energy through a mechanical system, do not result in a loss of energy and thus are known as non-dissipative components of impedance.

When the non-dissipative components of impedance are the same for a particular sound frequency, they cancel each other out, as seen in the equation in Figure 1, and at that time all the system's impedance depends only on the dissipative component (friction) and we say that the system enters into resonance, as the impedance is the minimum possible. In other words, at that particular frequency at which the components of mass and rigidity cancel each other out, the system allows the passage of sound energy better than at any other frequency.

These values are systematically determined in otorhinolaryngology departments using an admittance metering device. What usually happens is that the admittance metering devices only use one probe tone (generally 226 Hz), and to know the resonance frequency we need various tones to study how the dissipative and non-dissipative components behave at each of the frequencies utilized.

From the above we can understand that the admittance and impedance values in a mechanical system are not absolute values, but that they vary as a function of the sound frequency used in such a way that the difficulty posed by the ear to the passage of sound is not constant, but variable depending on the frequency studied. Thus, we used 4 probe tones: 226, 678, 800, and 1000 Hz.

Numerous studies show the mechanical-acoustic differences between normal and otosclerotic ears, which have higher resonance frequencies.¹⁷⁻¹⁹ These same findings are confirmed in our study.

The audiological results in the different groups of patients subjected to different techniques for stapedial fixation are similar in the groups studied, and there are no statistically significant differences between them 6 months after the procedure. At 6 months, the parameter that appears different in the 3 types of techniques studied is the mean auditory threshold by bone conduction, where the results were worse in the group in which stapedotomy was performed, even though the difference did not show statistical significance at the level chosen. Some authors²⁰ have highlighted the patient's age as the most important factor at the time of predicting the deterioration of bone conduction after stapedial surgery (specifically following stapedectomy). In our case, the average age of the group in which a stapedotomy was performed was lower.

The mechanical-acoustic results, however, are more similar to normality in those cases where the stapedial tendon was preserved than in the others. Thus we find that in the patients in whom the stapedial tendon was preserved and a vein inserted to replace the footplate, the mean resonance frequency a month after the procedure was between 800 and 1000 Hz (the same as in the normal control subjects), while it was lower in the other groups (678-800 Hz in the group in which the tendon was sectioned but a vein or perichondrium was inserted and >678 Hz in the stapedotomy group without any type of graft insertion), with a statistically significant difference. This finding (and those shown in other papers such as that by Schmerber et al,²¹ with better audiological results when a vein is used as a graft after stapedotomy with respect to the use of a perichondrium) leads us to select this type of graft as ideal for stapedial surgery.

In our opinion, this is due to the fact that, by preserving the stapedius tendon, the parameters determining the mechanical-acoustic qualities of the middle ear (mass and rigidity) are retained in a way similar to that which occurs in normal subjects. This is the conclusion reached by authors who, after studying this same subject, have reached similar results.^{13,15,22}

The fact that the resonance frequency in these patients is displaced towards high-pitched frequencies has 2 complimentary but fundamental audiological consequences: improvement in terms of the intelligibility of words in silence as well as the discrimination of language in noisy environments in order to facilitate the passage of high-pitched sounds over low-pitched ones. This fact was already confirmed by some authors^{15,23} after carrying out admittance testing in noisy environments on patients subjected to stapedectomy with the tendon preserved, which moreover elevated their discomfort threshold.²⁴ The effects of sectioning the stapedial muscle tendon are distortion of phase and frequency, as well as masking the sound at high frequencies, leading to worse sound discrimination.

On the other hand we have found that almost half (41.6%) of the patients in whom the stapedial tendon was preserved during the surgical treatment of otosclerosis presented a normal acoustic reflex 6 months after the procedure, which implies a greater defensive capacity of the ear vis-à-vis intense noises relative to those others in whom the tendon was sectioned during surgery. This fact has already been demonstrated by other authors.²⁵

If we compare the results in terms of resonance frequency between the 2 techniques that do not conserve the stapedial tendon, we observe that, by approaching better the results found in normal subjects, the technique which inserts a vein or perichondrium to replace the stapedius footplate is better than when the end of the piston is left free in the vestibule. This could be due to the fact that the insertion of an elastic material between the vestibule and the tip of the prosthesis mimics, at least partially, the elastic characteristics of the annular ligament.

If we qualitatively analyze the morphology of the conductance and susceptance curves in the ears of the subjects operated on, we observe that their morphology (narrow graph, presence of "peak-trough" and double, or triple hump traces) is closer to that of the control subjects the more conservative the approach has been with the structures of the middle ear and vice versa, in such a way that, in those patients on whom stapedotomy is performed without graft insertion in the oval, the curves present more distortions than in the rest of the cases.

The conservation of the stapedial tendon during stapedial surgery for otosclerosis permits the maintenance of mechanical-acoustic characteristics in the middle ear similar to those observed in normal subjects, which does not occur with the other techniques analyzed in this paper. As the audiological results obtained with this technique are comparable to those found in patients in whom the stapedial tendon was sectioned, this finding leads us to consider the preservation of this structure as necessary in stapedial surgery, not as an artifice of surgical virtuosity, but as a

substantial functional improvement in the surgical treatment of otosclerotic patients.

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