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Evaluation of Eardrum Laser Doppler Interferometry as a Diagnostic Tool

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Objectives: **Laser Doppler interferometry (LDI) of the eardrum allows noncontact optical analysis of its vibrations in response to sound. Although LDI has been widely used in research, it has not yet been introduced into clinical practice as an adjunctive test for otological workup. The aim of this study was to evaluate LDI as a diagnostic tool in the clinical sphere.** ***Study Design:*** **Prospective.** ***Methods:*** **A measurement system was developed based on a commercially available scanning He-Ne laser Doppler interferometer. The study included 129 eardrums of 79 subjects that were divided into 3 groups: 1) normal subjects and 2) patients with sensorineural and 3) conductive hearing loss (HL). All the patients suffering from conductive HL underwent ossiculoplasty, which allowed confirmation of the final diagnosis, and patients were assigned accordingly to the subgroups malleus fixation, incus luxation, and stapes fixation.** ***Results:*** **The modified LDI system allowed bilateral evaluation of a subject within 30 minutes. No significant difference between normal subjects and patients having sensorineural HL were found. However, it was possible to distinguish between normal subjects and patients with conductive HL. Furthermore, the system had the ability to differentiate between various middle ear diseases. These groups differed statistically significantly in terms of manubrium vibration amplitude and resonance frequency. In malleus fixation significant differences in tympanic membrane movement patterns were found.** ***Conclusions:*** **Our LDI is applicable in clinical otological practice and serves as a valuable addition to the routine audiological investigations for preoperative evaluation of the mobility and integrity of the ossicular chain.** ***Key Words:*** **Middle ear mechanics, laser Doppler interferometry, otosclerosis, malleus fixation, incus luxation, conductive hearing loss.**

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INTRODUCTION

The laser Doppler interferometer (LDI) is a device that allows noncontact optical analysis of vibrating objects with high accuracy in terms of amplitude and phase. It is possible to measure submicroscopic movements (in the nanometer range) of the tympanic membrane (TM) that occur when it is stimulated with sound. The LDI has been widely used in research to explore the function of the middle ear in animals, human cadaveric temporal bones (TB)[1–10] and, in some studies, even in live human subjects.[2,7,11] Its potential to diagnose otological diseases has been documented, because of its accuracy, reproducibility, high resolution of scanning, and the ability to obtain measurements without touching the object.[3] However, it has not yet been introduced in clinical practice as an adjunctive test for otological work-up.

The routine audiological test battery is of invaluable diagnostic value but does not always allow determination of the final diagnosis of conductive hearing disorders. Particularly, patients with isolated ossicular disease[12] can often be diagnosed only by a middle ear exploration. Tympanometry has the ability to identify middle ear effusion and TM perforation with high sensitivity and specificity[13] but is generally not sensitive enough to diagnose ossicular diseases.[14]

It was the aim of this study to evaluate the LDI as a diagnostic tool in the clinical sphere. The study was designed to answer the following questions: 1) Are LDI measurements practicable? 2) Can sensitive parameters be identified to distinguish different diseases? 3) Can additional information beyond the standard audiological tests be obtained?

MATERIALS AND METHODS

Patient Selection

All subjects were evaluated by pure-tone audiometry, impedance-and-reflex audiometry and micro-otoscopy before LDI measurements. The study included 79 subjects who were divided into three groups corresponding to their clinical diagnosis: 1) normal subjects (control group) and 2) patients with sensorineural and 3) conductive hearing loss (HL) (Table I). Informed consent was obtained for all the subjects. The inclusion criteria for the control group were normal otoscopy, air conduction thresholds in both ears within the limits of 25 dB HL, and a type A

TABLE I. Study Groups.			
Study Groups	No. of Patients	No. of Measured Ears	Age (min–max)
Normal subjects	45	90	26 (23–38)
Sensorineural HL	7	11	45 (30–72)
Conductive HL	27	28	38 (19–67)
Total	79	129	32 (19–72)

HL = hearing loss.

tympanogram. All 45 subjects in the control group were evaluated bilaterally. The sensorineural HL group included three patients with presbycusis, one patient with hereditary HL, and three patients with a sudden idiopathic HL. All of these patients had at least a moderate HL (threshold >40 dB HL) and no air-bone gap. All the patients with conductive HL had an air-bone gap of 30 dB or more and absent acoustic reflexes. Normal type A tympanograms were present in 10 patients, shallow type A tympanograms in 13 patients, and deep type A tympanograms in 5 patients (Table II). All these subjects underwent ossiculoplasty, which allowed us to determine the final diagnosis, and the patients were assigned accordingly to the subgroups "otosclerosis," "total malleus fixation," and "incus luxation" (Table II).

Measurement Set-up

A measurement system was developed based on a scanning He-Ne laser Doppler interferometer PSV200 (Polytec GmbH, Waldbronn, Germany). The sensor head and the scanning unit were suspended from a balanced operating microscope stand (Contraves, Zurich, Switzerland). A built-in camera and a computer-driven mirror system controlled the laser (spot size, 10 μm) position on the object with a spatial resolution of 5 μm. A loudspeaker (ER-2, Etymotic Research, Elk Grove, IL) produced the acoustic stimulus, which was controlled by a probe microphone (ER-7, Etymotic Research). A multisine tone was used for stimulation. The signal contained 31 frequencies between 500 and 8000 Hz that were produced by a signal generator (HP-33120A; Hewlett Packard, Palo Alto, CA) and a power amplifier (Revox A78, Bassersdorf, Switzerland). The sound pressure level was calibrated by the computer software (Polytec HLV 1.01, HP 34811A Benchlink, Macro on Microsoft Excel; Microsoft, Redmond, WA) to be 80 dB sound pressure level (SPL) for each single stimulation frequency, resulting in a total sound pressure of the stimulus of 94 dB. The LDI software (Polytec PSV 200) allowed convenient analysis of the recorded data for each single frequency of the multisine tone. It yielded three-dimensional animation and isoline amplitude view of the measured area. These functions were used to qualitatively assess the vibration mode of the TM. The data were also exported to other computer programs for further statistical analysis. Coherence between the stimulus and the laser response is a measure for the accuracy of an LDI measurement analogous to the signal-to-noise ratio and was computed by the PSV software. For the analysis, only results with a coherence of 90% or better were used. However, signal-to-noise ratios were also calculated and, typically, values of 10 to 25 dB were found. The threshold sensitivity of this LDI is 300 nm/s, which equals displacement amplitudes of less than 100 pm over all frequencies. The primary measurement result of LDI is velocity. Velocity amplitudes were used for most of the analyses in this study and are given in the graphs. However, because displacement amplitude, which can be calculated from velocity, is widely used in the literature, displacement results were also computed and are reported later in this study.

For each TM the following parameters were generated: 1) complex averaged velocity of all measured points on the TM, 2) velocity amplitude of the umbo, 3) displacement amplitude of the umbo, and 4) dominant resonance frequency of the umbo.

Experimental Method

A silicone tube probe microphone and a loudspeaker was placed in the ear canal through a custom-made ear speculum so that the tip of the tube microphone had a distance of less than 3 mm to the center of the eardrum. The ear speculum was held in place by means of ear-molding material (Otoform-A/Flex, Dreve-Otoplastik GmbH, Unna, Germany) and the head of the subject was held steady by a vacuum pillow. No reflective material was needed on the object. The actual measurement procedure was then performed. The mean duration was 50 to 90 seconds depending on the number of scanning points selected. For each point of a "measurement set," amplitude and phase of the vibration and its coordinates on the video capture were recorded in quick succession for further analysis, controlled by the PSV 200 software.

Because of the curved shape of the ear canal, the TM was not entirely visible in all subjects. Bony overhangs at the anteroinferior canal wall covered 30% to 40% of the TM area. However, umbo and short process of the malleus were both measurable in all subjects. On average, 95 points were analyzed on the TM surface in each subject. The measurements had to be interrupted in one subject because of uncomfortable sensations from the sound stimulus. This patient had a sensorineural HL with decreased loudness discomfort level and had to be excluded from the study. All other patients did not complain of any discomfort during or after the measurement.

Statistical Methods

To perform statistical analysis of the data in this study, three different tests had to be used. To test whether the groups and subgroups differed significantly in terms of vibration response to sound stimuli, a nonparametric Mann-Whitney rank sum test was applied. To compare the different published studies to our results, Student *t* test was used for individual frequencies because only mean and standard deviations were available from the literature. To analyze the tympanometric data of the patients

TABLE II.
Intraoperative Confirmed Diagnosis of Patients With Conductive Hearing Loss and the Corresponding Tympanometric Results.

Intraoperative Diagnosis	Type A Tympanogram	Type A_s Tympanogram	Type A_d Tympanogram	No. of Measurements
Otosclerosis	6	10	3	19
Bony malleus fixation	2	3	0	5
Incus luxation	2	0	2	4
Total	10	13	5	28

with conductive hearing loss, χ^2 χest was performed. In all tests, $P < .05$ was considered statistically significant.

RESULTS

Practicability

The modified LDI system allows bilateral TM evaluation of a subject within 30 minutes. Because of the mounting of the heavy (12 kg) sensor head onto a balanced operating microscope stand, the unit is easily movable in three dimensions and allowed simple assessment of the TM.

Tympanic Membrane Vibration Mode

The eardrum moves in phase in all subjects up to the resonance frequency. The posterosuperior quadrant moves most and the manubrium moves least up to the resonance frequency in all subjects except in patients with a luxated incus. In these patients the manubrium and the TM vibrate at comparable amplitudes. At higher frequencies the different parts of the TM move at different phase but with similar amplitudes.

Figure 1 shows isoline graphs of a representative normal subject at 700 Hz and 1700 Hz in response to 80 dB SPL. Between two isolines, differences of 3 dB amplitude and 90° of phase are illustrated, respectively (Fig. 1). Figure 1A shows the TM displacement pattern at 700 Hz. At the posterosuperior quadrant a maximum was present, and a minimum at the superior manubrium. The difference between minimal and maximal vibrating points was a factor of 8 corresponding to 18 dB. In Figure 1B, no lines are present at 700 Hz because the entire TM moved in phase. At 1700 Hz several peaks occurred (Fig. 1C) because different areas of the TM moved out of phase (Fig. 1D). For illustration of TM measurement, results of a representative normal subject are shown in Figure 2. Figure 2A shows the velocities of a TM measurement set. Each individual velocity of the 229 measured points was plotted. The maximum response that equals the resonant frequency was found at 1150 Hz. Velocity differences of up to a factor of 5 (14 dB) were measured on diverse parts of the TM. In Figure 2B the phase difference between umbo and each point of the measurement set is given. These points had small phase differences up to the resonance frequency. At higher frequencies the phase differences were dispersed over one entire cycle.

Tympanic Membrane Vibration Amplitude

For all subjects the complex averaged velocity (CAV) of the TM was calculated for the different frequencies. In contrast to the absolute average, this parameter is smaller because it takes the phase difference between single points into consideration and is proportional to the volume velocity. Figure 3 includes the CAV of the TM at 80 dB SPL and the standard deviation for the control group. Also included are the CAV values for all subgroups. The total malleus fixation group had statistically significant ($P < .05$) lower velocities at frequencies up to 1400 Hz. However, no significant differences between normal subjects and the other subgroups

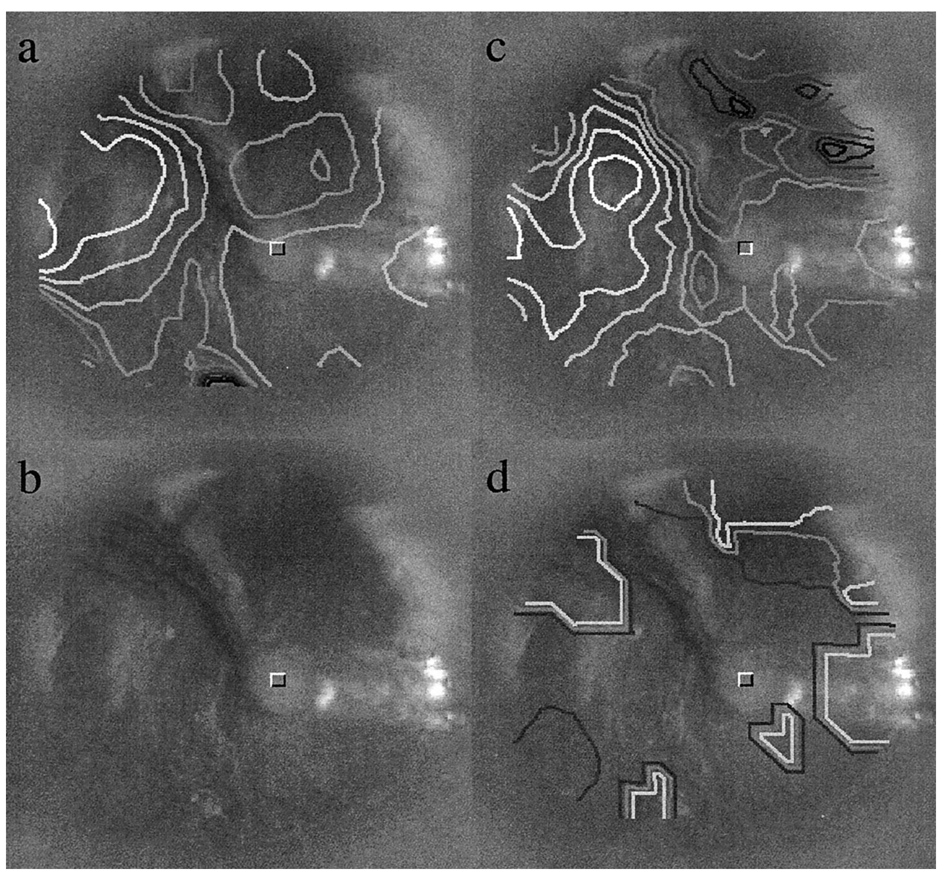

Fig. 1. Isoamplitude and isophase lines on a representative right-side tympanic membrane (TM) of a normal-hearing subject in response to 80 dB sound pressure level (SPL). The square marks the umbo; posterior is on the left side. (**A**) Displacement magnitude at 700 Hz. Each contour line represents a displacement difference of factor 1.4 (3 dB). Displacement magnitude at the umbo is 13 nm. (**B**) Displacement phase at 700 Hz. The missing contour lines indicate that no phase difference is present and the entire TM vibrates in phase. (**C** and **D**) Displacement magnitude and displacement phase at 1700 Hz, respectively. Each contour line represents a displacement difference of factor 1.4 (3 dB) and a phase difference of 90°, respectively. The contour lines demonstrate that different areas of the TM move out of phase. Displacement magnitude at the umbo is 7 nm.

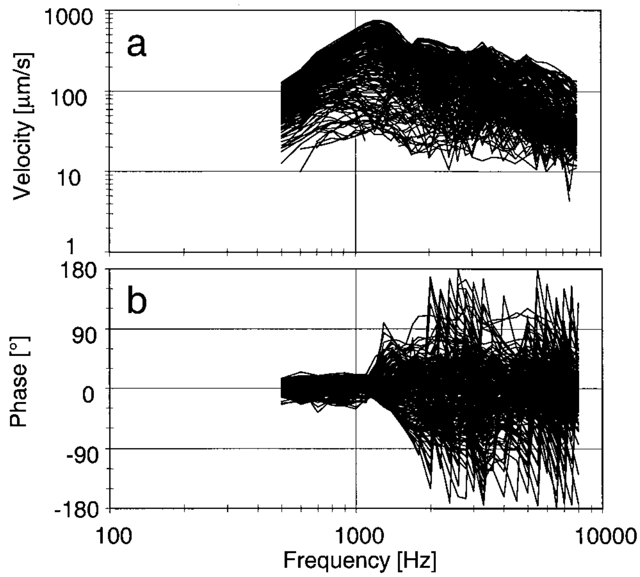

Fig. 2. (**A**) Velocity of 229 equally dispersed points on the tympanic membrane in response to 80 dB SPL and (**B**) phase difference between umbo and any point of the measurement set in one representative normal-hearing subject.

were found according to the nonparametric Mann-Whitney rank sum test.

Umbo Vibration Amplitude

In the control group there was a considerable range of umbo amplitudes. At each individual frequency a factor of 3 to 6 (10 to 15 dB) was present. Figure 4 includes the mean displacement response at 80 dB SPL and the standard deviations. The displacement was constant up to the resonance frequency and sloping at the higher frequencies. The first umbo resonance frequency of the control group was determined for each individual. It was at 900 Hz on average with a standard deviation of 300 Hz (Fig. 5).

No statistically significant differences between normal subjects and patients with sensorineural HL were found ($P > .05$) by evaluating umbo vibration amplitude and resonance frequency using nonparametric Mann-Whitney rank sum test.

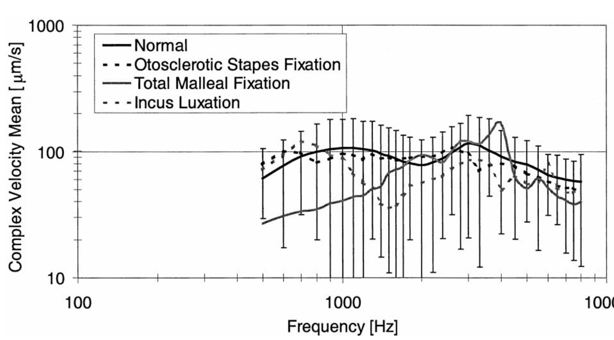

Fig. 3. Complex averaged velocity of the scanned TM in response to 80 dB SPL in normal-hearing subjects and patients with conductive hearing loss (n = 118 ears). Bars represent 1 SD.

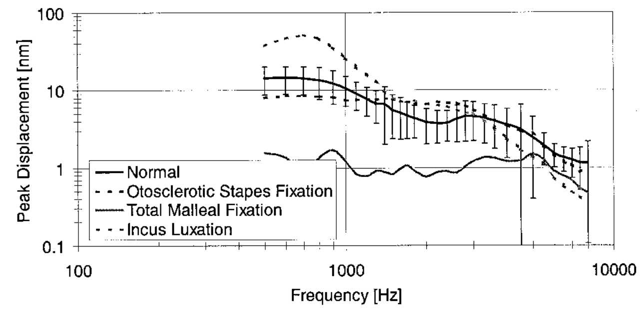

Fig. 4. Umbo displacement in response to 80 dB SPL for normal-hearing subjects and patients with conductive hearing loss (n = 118 ears). The bars represent 1 SD for the control group.

Figure 4 includes the averaged displacement amplitudes of the conductive HL subgroups. The total malleus fixation patients differed most from the control group. A difference greater than a factor of 10 (20 dB) was present at the low and mid frequencies, whereas at higher frequencies the difference was only a few decibels. The patients with incus luxation showed substantially higher vibration amplitudes at low and mid frequencies. The otosclerosis subgroup presented the smallest difference from the control group. However, there was a statistically significant difference ($P < .05$) of all subgroups compared with the control group at most frequencies according to nonparametric Mann-Whitney rank sum test: The otosclerotic group differed statistically significantly at low frequencies up to 1000 Hz and at 1500 Hz to 2800 Hz, the total malleus fixation group over all frequencies except 4500 Hz, and the incus luxation group at frequencies up to 1500 Hz and higher than 5500 Hz.

The velocity in response to constant sound was used to display the first dominant resonance (mean and standard deviation) for the control group and subgroups (Fig. 5). These differed statistically significantly ($P < .05$) between the control group and the patients with otosclerosis, as well as those with total malleus fixation. No difference in dominant resonance frequencies ($P > .05$) occurred between the control group and the incus luxation group,

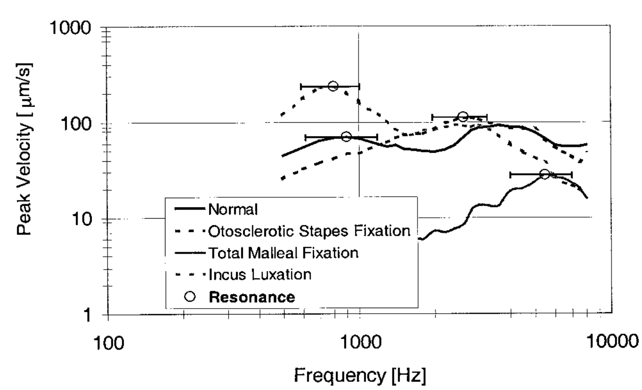

Fig. 5. Umbo velocity in response to 80 dB SPL for normal-hearing subjects and patients with conductive hearing loss (n = 118 ears). The mean and SD values for the first resonance frequency are marked.

according to the nonparametric Mann-Whitney rank sum test.

DISCUSSION

Various methods for accessing vibration in response to acoustic stimulation have been used in the past. With most of these techniques, some sort of contact with the vibrating surface is required for measurements; therefore, they are not practical for measurements in live humans. Besides LDI, only holography allowed measurements in live human subjects,[15,16] although the technique is time-consuming and not as sensitive as LDI. At present, LDI appears to be the most accurate and reliable and the safest method for evaluating vibration in live human ears. However, until the present, no systematic comparison of measurements in normal subjects and patients with HL was published considering the clinical value of this technique.

Practicability

Laser Doppler interferometry is a noninvasive and reliable method for assessment of the TM vibrations. In all but one subject results could be obtained, and the measurements were acquired within a reasonable time. Our modified LDI system is applicable in the clinical sphere. However, the high price of a scanning LDI system at this time limits its value for use in the routine clinical practice.

Normal Subjects

The vibration patterns (Fig. 1) of the normal TM are in agreement with earlier published measurements of the eardrum deflection shape in temporal bone preparations.[6,9,17–19] Figure 3 shows the complex velocity average of the measured TM area. The volume velocity that represents the displaced volume can be calculated from average TM velocity and TM area. However, the exact volume velocity cannot be computed from our data because only 60% to 70% of the TM is accessible for measurements, because of bony overhangs of the external auditory canal. The area that is not accessible for measurements is located close to the tympanic ring anterior and inferior that is virtually not vibrating. Therefore, the average TM velocity is most likely overestimated in this study. However, more accurate measurements are not possible in normal human subjects by direct measurements. Average TM velocity of live human subjects is published in this study for the first time.

Figure 6 compares umbo displacement of our control group in response to 80 dB SPL sound stimulus with the prior published LDI results in normal human ears.[3,11] Values were read from the graphs in these studies. Our results were similar in terms of frequency response to the results of the study of Goode et al.,[3] as well as to the study of Rodriguez et al.[11] According to the Student *t* test, our control group and the group of Goode et al.[3] was statistically equal at frequencies near 2000 Hz and 8000 Hz ($P > .05$). The maximal difference was approximately a factor of 1.7 (5 dB). Our results differed significantly (Student *t* test, $P < .05$) from the results of Rodriguez et al.[11] at all frequencies. The groups of Goode et al.[3] and Rodriguez et al.[11] were statistically equal at frequencies near 3000 Hz. We cannot pinpoint causes for these differences, but

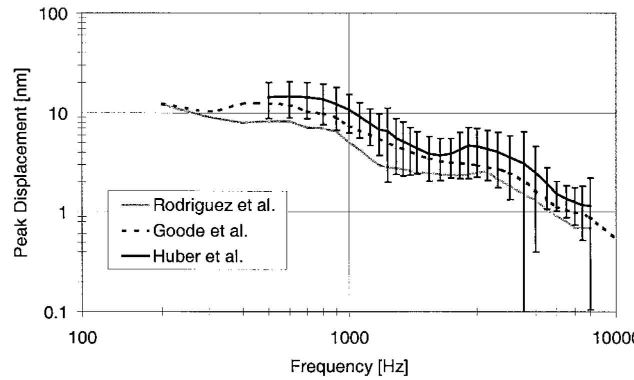

Fig. 6. Umbo displacement in normal-hearing live human subjects as reported in the literature (Goode et al., Rodriguez et al.) and found in this study (Huber et al.). All curves have been adjusted to an 80 dB SPL sound input. Bars represent 1 SD.

they may be attributable to the different experimental setups, in particular, the different sound stimuli.

Stapedius Reflex

The acoustic reflex is usually elicited at 80 to 90 dB SPL in normal ears and is absent in patients with middle ear disease. In patients with moderate to severe sensorineural HL the acoustic reflex is elicited at increased sound pressure. Before LDI measurements the elicitation of the acoustic reflex was tested in response to the sound stimulus used for LDI measurements at 94 dB SPL. The reflex was activated in all normal subjects but not in both groups of patients with sensorineural and conductive HL.

As a result of the acoustic reflex, the stapes is displaced posteriorly, because of contraction of the stapes muscle. Therefore, the annular ligament of the stapes is tightened, which increases the impedance of the stapes/cochlea complex and subsequently alters the TM vibration patterns. According to Svane-Knudsen and Michelsen[20] and documented in our own experiments, the umbo vibration response to a given sound stimulus is altered by less than 5 dB. Because of the acoustic reflex, the sensitivity to diagnose fixation of the ossicular chain is diminished in this method because the middle ear impedance is increased in normal subjects during the stapedius reflex but remains constant in patients with ossicular fixation. On the other hand, lower SPL that would not elicit the acoustic reflex would have led to less reliable results in terms of signal-to-noise ratios and to longer measuring time because multiple averaging became necessary or repeated single frequency stimulation methods had to be used.

According to our experience with 20 subjects before this study, who were stimulated with lower SPLs, we found it preferable to use the higher acoustic stimulus in favor of the practicability of the method, despite the diminished but still satisfactory sensitivity.

Measurement Angle

The LDI system records velocity amplitudes in the direction of the measuring laser beam. If the laser beam and the direction of vibration are not aligned, projection of the velocity is recorded. This projection is a cosine function of the angle between the direction of vibration and the laser beam. In the present study the angle between the measuring laser beam and a vector perpendicular to the plane through the tympanic annulus is estimated to be approximately 30°. Measurements are not angle corrected; therefore, the actual vibration amplitudes in the plane of the tympanic annulus are underestimated by a factor of 0.87 (1.2 dB). In addition, it must be considered that the TM is not flat but describes a curved membrane. Therefore, different parts of the TM may not be assessed accurately, and the results of the complex averaged TM velocity may be biased. However, these angles are relatively constant in all subjects and are constant over the frequencies during one measurement set. We expected the bias from the measurement angle to be small, and no angle correction was performed in the present study.

Sensorineural Hearing Loss

In our series we were not able to show statistically significant differences in results from normal subjects and patients with sensorineural HL. This is in contrast to the results of Rodriguez et al.[11] They reported the specific acoustic impedance of the umbo of one patient with minimal sensorineural HL. They observed that the specific acoustic impedance of the umbo resembled the hearing threshold curve in this patient and concluded that pathological umbo vibration patterns may indicate inner ear dysfunction. However, none of our measurements on 11 ears could verify correlation between hearing threshold and manubrium vibration.

Conductive Hearing Loss

Using LDI, it was possible to identify artificially produced conductive HL in human temporal bone preparations.[10,21] Vlaming and Feenstra[10] conducted studies on the mechanics of the normal human temporal bone with special reference to the damping and stiffening effect of the cochlea. They included measurements before and after disrupting the ossicular chain. After removing the incus, they found an increased vibration amplitude of the umbo at low frequencies by the factor 3 (10 dB) compared with the intact chain. A pronounced resonance peak was present at 850 Hz. Stasche et al.[21] found decreased umbo vibration amplitudes in a temporal bone preparation with an artificially fixed stapes and increased amplitudes in specimens with disrupted ossicular chain at low frequencies. The present study reports for the first time identification of surgically confirmed ossicular disease in subgroups of live human subjects. Normal middle ears, incus luxation, bony malleus fixation, and otosclerotic stapes fixation differed significantly in terms of manubrium vibration amplitude (Fig. 4) and resonance frequency (Fig. 5). The amplitude difference between normal ears and ears with ossicular fixation was between 5 dB and 25 dB. Therefore, LDI also has the potential to identify partial ossicular fixation.

Before surgery the exact diagnosis could only be presumed on the basis of the standard audiological tests. The subgroups did not differ in terms of audiograms or reflex audiometry. In impedance audiometry a tendency toward shallow type A tympanograms was present in the stapes and malleus fixation subgroups, and a tendency toward deep type A tympanograms in incus luxation subgroups. However, the groups' differences were not statistically significant according to χ^2 analysis.

The differences between normal and pathological vibration patterns were more significant the closer the measured target was located to the disease. Bony malleus fixation differed most, incus luxation less, and otosclerotic stapes fixation the least from normal umbo vibration. On the other hand, measurements on the umbo were more appropriate to determine ossicular disease than measurements of the TM. However, scanning LDI of the eardrum may be clinically useful to identify TM disease and to distinguish between "tin and gold ears."[22]

Future Studies

The future goals of diagnostic scanning LDI measurements of the TM are 1) to identify partial ossicular fixation as a possible cause of poor results after ossiculoplasty and thereby assist in improving hearing results after otological surgery, 2) to identify ears with acoustically inefficient TM (tin ears),[22] and to facilitate development of methods to improve their function.

CONCLUSION

Our LDI system is applicable in clinical otological practice. It has the ability to differentiate normal middle ears, stapes fixation, malleus fixation, and incus luxation before surgery. This was not possible with standard audiological tests. Single point measurements on the umbo were sufficient for identification of the ossicular disease. The LDI system serves as a valuable addition to routine audiological investigations for preoperative evaluation of the mobility and integrity of the ossicular chain.

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