

## INTRAOPERATIVE ASSESSMENT OF STAPES MOVEMENT

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A method is described that allows, for the first time, intraoperative vibration modes assessment of the acoustically stimulated stapes by means of scanning laser Doppler interferometry (LDI). The study was designed to answer the following questions: 1) Is LDI practical for taking measurements during surgery? 2) Are the results comparable to the findings in temporal bone preparations? and 3) Do the vibration characteristics of the stapes change after the posterior incudal ligament is detached from the incus? Seven patients with profound bilateral hearing loss who were undergoing cochlear implantation were included in the study. The measurement system was easily applicable for intraoperative measurements and allowed contact-free analysis with very high accuracy. No major differences in the results from the live human subjects and temporal bone preparations were observed. The stapes movement was predominantly pistonlike at the lower frequencies and became complex at higher frequencies. Sacrificing the posterior incudal ligament had no statistically significant effect on stapes vibration.

**KEY WORDS** — laser Doppler interferometry, middle ear mechanics, posterior incudal ligament.

### INTRODUCTION

Middle ear vibrations in response to physiological acoustic stimulation are in the micrometer and nanometer range of displacement and are therefore difficult to assess. During the 20th century, methods for analysis of these vibrations became more and more sophisticated and finally allowed contact-free measurements with very high accuracy. At the present time, laser Doppler interferometry (LDI) appears to be the most reliable method. Although LDI is frequently employed for research in animals, temporal bone (TB) preparations, and even tympanic membrane evaluation of human subjects, so far it has not been available for direct middle ear measurements in live humans during surgery. Without LDI, the surgeon uses an instrument to wiggle the ossicles under visual control with an operating microscope and qualitatively estimates the mobility of the ossicular chain. The goal of this research was to quantitatively measure the ossicular chain vibration during surgery.

The movement of the stapes in response to physiological sound has been described as a rotation around a fixed vertical axis running through the posterior edge of the footplate in human TBs.<sup>1</sup> On the other hand, a purely pistonlike movement was described in another study of human TBs<sup>2</sup> and in anesthetized cats.<sup>3</sup> Further measurements in human TBs<sup>4</sup> indicated that both a rocking motion and a superimposed pistonlike movement are present. Recent studies in human TBs<sup>5</sup> and anesthetized cats<sup>6</sup> confirmed these findings. So far, no measurements of the stapes

have been made in live human subjects, and it was the intention of the present study to focus on stapes measurements and compare the results to the findings in TB preparations.

In certain otologic operations, the posterior incudal ligament (PIL) has to be sacrificed to gain wider access to the middle ear. Although its acoustic function has been examined,<sup>1</sup> its importance for proper sound transmission is not known. It was a further goal of the present study to gain more information on the acoustic function of the PIL. The study was designed to answer the following questions: 1) Is LDI practical for taking measurements during surgery? 2) Are the results comparable to the findings in TB preparations? and 3) Do the vibration characteristics of the stapes change after the PIL is detached from the incus?

### MATERIALS AND METHODS

**Patient Selection.** The study included 7 patients with profound bilateral hearing loss who were undergoing cochlear implantation. Before surgery, all patients (or their parents) were precisely informed and consented to participate in the study. The mean age was 31 years (range, 3 to 69 years).

**Measurement Setup.** A measuring system was developed based on a scanning laser Doppler interferometer (Polytec GmbH, Waldbronn, Germany). The sensor head and the scanning unit were suspended from a standard operating microscope stand (Contraves, Zurich, Switzerland). A built-in camera and a

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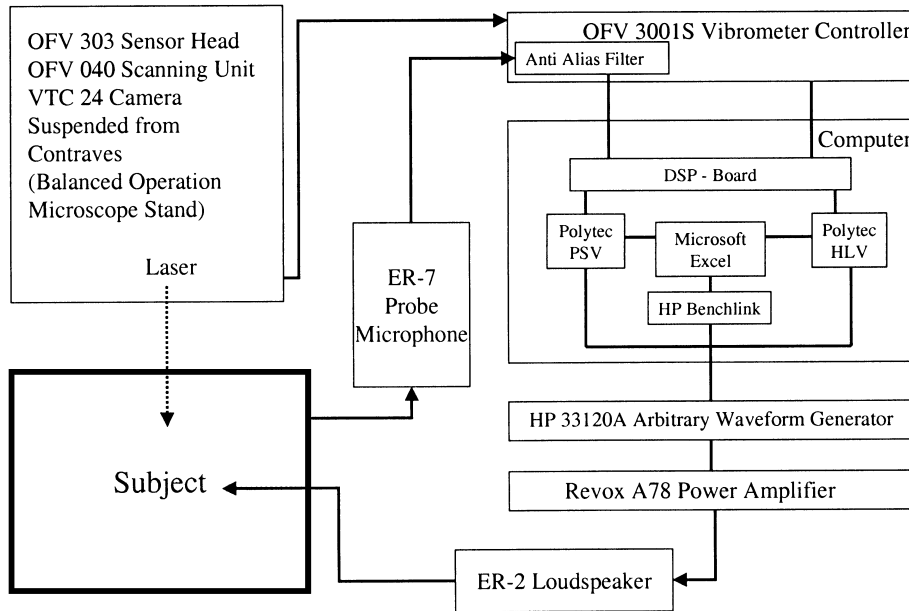


Fig 1. Measurement setup.

mirror system controlled the laser position on the object (Fig 1). A loudspeaker (ER-2, Etymotic Research, Elk Grove, Ill) placed in the external auditory canal produced the acoustic stimulus, which was controlled by a probe microphone (ER-7, Etymotic Research) close to the tympanic membrane. A multisine tone was used for stimulation. The signal contained 31 frequencies between 500 and 8,000 Hz that were produced by a signal generator (HP-33120A, Hewlett Packard, Palo Alto, Calif) and a power amplifier (Revox A78, Zurich, Switzerland). The sound pressure level (SPL) was calibrated by computer software (Polytec HLV 1.01, HP 34811A Benchlink, Microsoft Excel) to be 80 dB SPL for each stimulation frequency, resulting in a total sound pressure 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 3-dimensional animation and an iso-amplitude line view of the measured area. These functions were used to qualitatively assess the vibration mode of the stapes (rotatory versus translatory and rigid body versus bending). The data were also exported to other computer programs for further statistical analysis. Coherence is a measure of the noise level of an LDI measurement and was computed by the PSV software. For the analysis, only results with a coherence of 90% or better were used; this represents a signal-to-noise ratio of typically 10 to 25 dB.

**Experimental Methods.** The sterile probe microphone and loudspeaker were placed in the ear canal before surgery so that the tip of the tube microphone was less than 3 mm from the center of the eardrum. The ear canal was then plugged with a soft foam ear-tip (Etymotic Research). Once the facial recess was

opened by the surgeon (Fig 2), the LDI system was positioned in such a way that the stapes (and, if possible, its footplate) was visible on the LDI built-in camera. The laser beam was aimed through the posterior tympanotomy onto the stapes, and the angle between the beam and the footplate was estimated. The multisine tone was generated and calibrated, and scanning measurements of the stapes vibration amplitude were performed as a baseline. The buttress (which is the bony bridge that remains after a posterior tympanotomy, connecting the lateral semicircular canal wall and the posterior auditory canal wall) was then carefully removed, and the PIL was sacrificed. However, the anatomic position of the incus was unchanged, and it was supported by medial fibers of the PIL that remained intact. The tympanic membrane also remained intact during the procedure. The operating microscope and the LDI could not be in position simultaneously, so that the LDI had to be

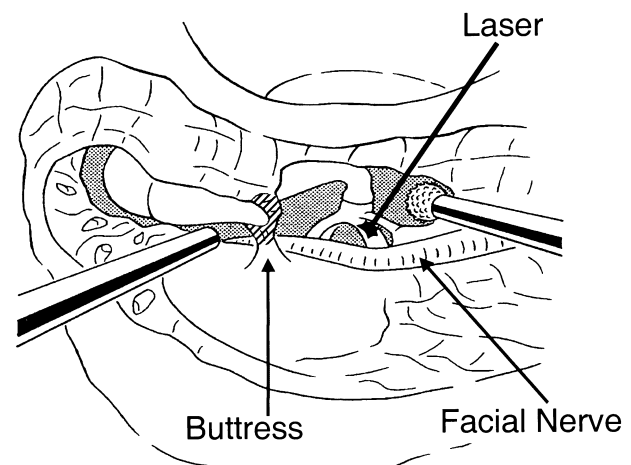


Fig 2. Schematic view of intraoperative measurement.

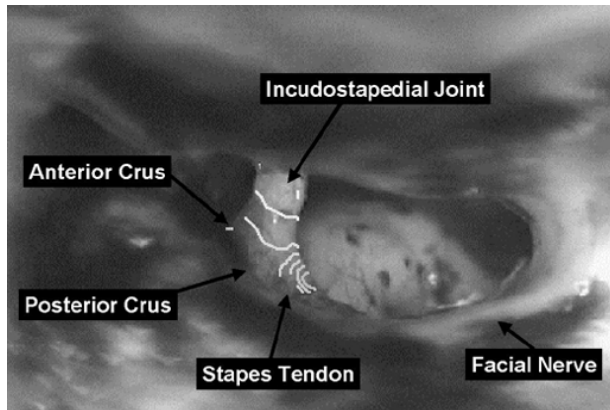


Fig 3. Stapes vibration seen through facial recess, graphically plotted as iso-amplitude lines at stimulation frequency of 500 Hz and 80 dB sound pressure level. Complex but mostly pistonlike movement is represented, with little rotational movement around long axis of stapes footplate and decreased movement at stapes tendon.

repositioned before the next measurement. The assessment of the stapes vibrations was then repeated, and the angle between the laser beam and the footplate was estimated again. For each measurement, a mean of 203 points (range, 69 to 295) was recorded on the stapes, incus, and promontory. The study included a mean of 20 (range, 7 to 31) reliable (signal coherence of 90% or higher) points on the stapes for each measurement.

## RESULTS

**Practicability.** The experiment was performed within 10 to 15 minutes, including installing and aiming of the measuring system, calibration of the sound, and the scanning interferometry itself.

Figure 3 shows a representative measurement result of stapes vibration in one subject. Plotted are iso-amplitude lines at a stimulation frequency of 500 Hz and 80 dB SPL on the video image of the measured area. Each line represents an amplitude difference factor of 1.2. The highest vibration amplitude was found at the stapes head (1.9 nm), and the lowest was found at the stapes tendon (0.6 nm). Three-

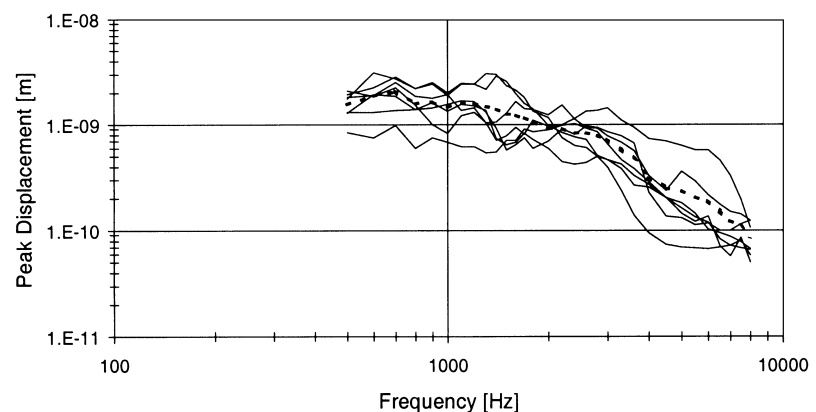
dimensional animation was used to qualitatively assess the vibration mode that showed complex but mostly pistonlike movement and no bending. At this frequency, the amplitude difference along the stapes only led to modest rocking.

Unlike in TB preparations, in live surgery the facial nerve is intact and limits the view of the stapes footplate. Therefore, in only 2 patients was the stapes footplate accessible to the laser. In the other 5 cases, the vibrations of the stapes superstructure were measured. The angle between the laser beam and an imaginary axis perpendicular to the stapes footplate was estimated to be 30° to 40° in all experiments, but did not differ by more than 10° in the same patient after repositioning of the LDI system.

**Baseline Stapes Movement.** Figure 4 shows the baseline displacement amplitudes of the stapes center in 7 cases. No angle correction was performed for the results. The peak displacement was approximately 2 nm in the frequencies below 1,000 Hz. The range was a factor of 3 to 10 (10 to 20 dB) over all frequencies. The repeatability within two readings of the same patient varied by about a factor of 1.12 (1 dB) when the LDI system was repositioned. By 3-dimensional animation of the data, the vibration mode of the stapes was found to be mostly pistonlike at lower frequencies up to about 1 kHz. At higher frequencies, a superimposed rocking motion became more dominant.

**Posterior Incudal Ligament.** In Fig 5, the mean stapes displacement amplitudes are plotted for baseline and a detached PIL. Although a minor increase in vibration amplitudes at lower frequencies and a slight decrease in vibration amplitudes at higher frequencies was found, these observations did not reach statistical significance according to the Mann-Whitney test. The maximum difference of the mean was a factor of 1.4 (2.9 dB) at 6,000 Hz. A difference factor of 0.6 to 1.8 ( $\pm 5$  dB) was not exceeded by any subject. Figure 5 also includes recently published measurements of 22 TB preparations performed with

Fig 4. Baseline displacement amplitude of stapes center (individual subjects and mean;  $n = 7$ ).



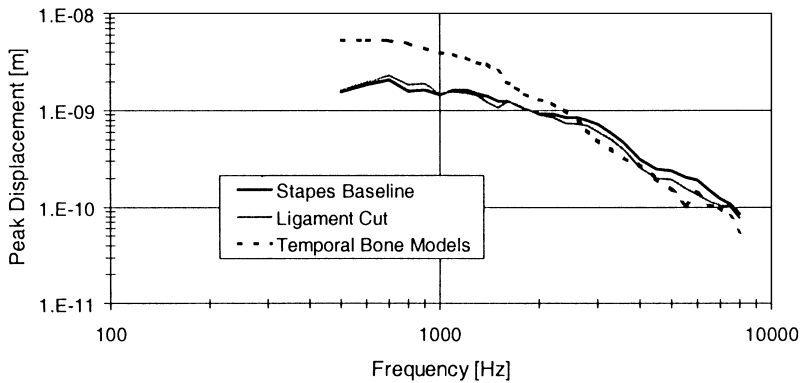


Fig 5. Mean stapes displacement amplitudes at baseline and after detaching posterior incudal ligament, and amplitudes of 22 temporal bone<sup>7</sup> preparations.

a similar technique through the facial recess.<sup>7</sup> The results differed at frequencies lower than 2,000 Hz and higher than 4,500 Hz by a maximum factor of 3 (10 dB).

## DISCUSSION

**Practicability.** Our measurement system was easily applicable for intraoperative middle ear assessment, with only minimal prolongation (<15 minutes) of the surgery. The heavy sensor head and the scanning unit (12 kg) were suspended from a balanced operating microscope stand and were therefore comfortable for positioning. The laser light was sufficiently reflected from the object without any targets. Adequate signal-to-noise ratios and satisfying coherence of the signal were obtained.

**Baseline Stapes Movement.** In Fig 5, intraoperative stapes displacement measurements are compared to the results of 22 TB preparations. Although TB preparations are believed to exactly mimic the function in live humans, the postmortem effects caused by inner ear pressure change, tissue edema, temperature change, humidity, etc, cannot be ruled out. Guinan and Peake<sup>3</sup> concluded that stapes modes of vibration differ significantly in cadaver TBs and anesthetized cats and hypothesized that this difference is due to postmortem changes. Goode et al<sup>8</sup> found no difference in umbo vibration of live humans and TB preparations. With our method, it was for the first time possible to quantitatively assess in vivo the displacement amplitudes of the human stapes, which define the input into the inner ear, and to compare them to the results of cadaver TB experiments.

The results of intraoperative and TB experiments differed by less than 10 dB at low frequencies, and by less than 5 dB at high frequencies. Because the middle ear was unphysiologically opened to ambient air in the present study, the stapes vibrations are expected to be biased. On increasing the middle ear volume, Gyo et al<sup>9</sup> found improved sound transmission at lower frequencies (lower than 1 kHz) and decreased sound transmission at middle frequencies

(1.5 to 4 kHz). According to these experiments, our results may be overestimated at lower frequencies and underestimated at higher frequencies by some decibels because of the lowered stiffening effect of the middle ear cavity. This effect adds to the difference between live human subject and TB experiments. On the other hand, the results from both the TB preparations and live humans are not angle-corrected. The measurement angle is almost perpendicular to the stapes footplate in the TB preparation because of the sacrificed facial nerve and the shortened posterior canal wall. This leads to a more accurate assessment of the stapes movement and higher displacement results. Further, the age groups of the studies do not match. The mean age was 74 years in the TB study and 31 years in this study. Although no statistically significant correlation of umbo vibration amplitude and age was found, young subjects tended to have a stiffer frequency response in a study by Goode et al.<sup>8</sup> This, again, may have led to a smaller displacement result in the present study. The differences, however, are in relation to the range of inter-individual differences, which was approximately 10 to 20 dB in this study (Fig 4). We conclude that the TB is an adequate model for studying middle ear mechanics.

The stapes vibration was mainly pistonlike at lower frequencies and complex at frequencies above 1 kHz. This observation is in accordance with historic<sup>4</sup> and recent<sup>5</sup> studies in TBs and a recent study in anesthetized cats.<sup>6</sup> On the other hand, purely pistonlike<sup>3</sup> and purely rotational<sup>1</sup> forms of stapes movement were found over all frequencies by earlier authors. These measurements were performed with methods that did not allow the high level of accuracy afforded by modern LDI. Therefore, this discrepancy can be explained by the measurement sensitivity, especially at higher frequencies. Also, LDI measurements<sup>2</sup> have led to the conclusion that the stapes moves in a purely pistonlike way. In that study, the measured variability of different points on the stapes footplate was found to be up to 2 dB in amplitude and 20° in phase. This variability was described as due to the inaccuracy of

the method and was less than in the present study. However, this variability could also represent significant rocking.

In accordance with experiments on stapes vibration in the TB,<sup>5</sup> no bending of the stapes was found at any frequency — a finding indicating rigid body behavior.

**Posterior Incudal Ligament.** The LDI measuring direction was not at right angles to the stapes footplate. If the major movement is assumed to be perpendicular to the stapes footplate, a systematic underestimation of the displacement amplitude in the range of 1 to 3 dB occurs. The measurement angle within each experiment, however, did not differ by more than 10°. The bias for assessment of the acoustic function of the PIL is therefore less than 1 dB and can be ignored. The stapes reflex was not induced during the experiments, because of the severe hearing loss of the subjects, and thus did not influence the trial.

The mean displacement amplitude of the stapes was not influenced by more than 2.9 dB by cutting of the PIL. All else being equal, this 2.9 dB represents a statistically nonsignificant ( $p > .05$ ) change of the middle ear transfer function. The results are in accordance with the qualitative findings of von Békésy,<sup>1</sup> who did not find differences in middle ear transfer caused by cutting the PIL. This outcome im-

plies that the PIL can be sacrificed during ear surgery without the risk of impairing the postoperative hearing result. However, this experiment does not take into consideration any of the postoperative changes (eg, scarring of the remaining PIL fibers) that may have an important impact on postoperative hearing.

Possible future applications of our intraoperative scanning LDI system are 1) assessment of stapes mobility in chronic ear surgery as a selection criterion for the best technique of hearing reconstruction, 2) quantitative detection of ossicular fixation in patients suffering from conductive hearing loss to assist in improving hearing results after surgery, 3) intraoperative quality control of ossiculoplasties and active middle ear implants, and 4) verification and improvement of mathematical middle ear models.

## CONCLUSIONS

The described measurement system is easily applicable for intraoperative measurements and allowed for the first time quantitative assessment of the movement of the acoustically stimulated stapes with high accuracy during surgery. There are no major differences in terms of stapes vibration in live human subjects and cadaver TB preparations. Sacrificing the PIL has no immediate statistically significant effect on the middle ear transfer function.

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