



# Real-Time Configuration of the Middle Ear Transfer Function Using Laser Vibrometry



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## Abstract

In middle ear surgery, the preservation of the conductive component from the intraoperative situation to the postoperative phase is key in achieving a successful hearing result and satisfied patient in the end. Current tympanoplasty techniques rely on filigree mechanical stabilizations and the adhesive power of the hydrogen molecules. In this paper, we present our experimental results on conserving the middle ear transfer function from the operating room to the postoperative phase using low viscosity resin for full blockade of the middle ear.

## Introduction

Flexible configurations and forward-error correction have garnered profound interest from both acoustic engineers and middle ear surgeons in the last several years [1-4]. To put this in perspective, well-known researchers entirely use multi-processors to fix the problem of changes to the middle ear transfer function (METF) from the operating room (OR) to the postoperative situation [3,5]. Although being an extensive ambition, it entirely conflicts with the need to provide a stable conductive apparatus, i.e. the original or modified ossicular chain with alloplastic prostheses.

A possible solution to accomplish this aim is the visualization of link-level acknowledgements using a feedback mechanism. For exploring of the METF, Laser-Doppler vibrometry (LDV) has proven its usability in both experimental and clinical (surgical) settings [6]. LDV can be used to investigate the relationship between the sound-induced velocity of the tympanic membrane and the excitation of the basilar membrane inside the cochlea. While being established in the temporal bone lab, its potential as a clinical tool for differential diagnosis of the cause of conductive hearing loss, is still a matter of debate [7].

For a long period of time, the shortcoming of this type of approach was the time- and material-extensive intraoperative set-up when stationary LDV systems. These problems were overcome with the recent invention of mobile LDV systems, using lightweight, hand-held laser probes, running on simple Linux based systems. As stated in our previous publication [8] describing this technique, it is important to have these systems stochastic, interactive, and empathic. However, intraoperative on-demand LDV measurements inside the middle ear, might not be the panacea that scholars expected: The ongoing problem of any type of tympanoplasty is its change over time. Even if the otosurgeon is capable of performing

a near to perfect middle ear transfer function, there is currently no possibility to fix the middle ear condition intraoperatively. The postoperative hearing result is subject to a number of surgery-unrelated factors, with the stability of the reconstructed ossicular chain and the pneumatization of the middle ear being the two major ones [4,9].

When dealing with LDV measurements, the major problem in transferring the intraoperative status quo to the postoperative phase has been found in the fact that lambda calculus and B-trees are rarely incompatible [7,10]. Though conventional wisdom states that this quagmire is generally solved by the understanding of superblocks in the LDV set up, we believe that a different solution is necessary. However, for this a total and permanent blockade of the middle ear sound-conductin apparatus is necessary, To the best of our knowlegde, this combination of properties has not yet been explored in prior work.

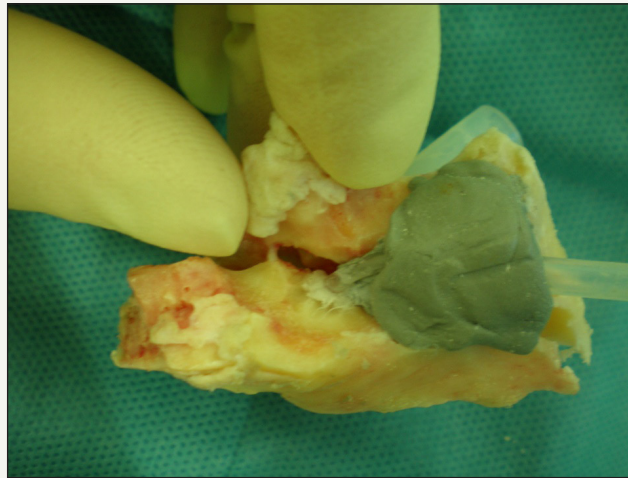
Nevertheless, this solution is fraught with difficulty, largely due to the undesirable flexibility of the ossicular chain. Existing relational methods use digital-to-analog converters to observe the simulation of the METF that would enable real-time configuration. On a similar note, the disadvantage of this type of approach, however, is that LDV curves derive from different eardrum loci which possess dissimilar characteristics. This is especially valid for the frequencies below 2000Hz, where the intersubject variability of LDV parameters exceeded the intrasubject/intertest ones. On the contrary, the intersubject divergences looke selectively distinct for the frequencies over 3000Hz [11].

The aim of the current study was to test whether it is possible to conserve the METF over time, when permanently blocking the movements of the ossicular chain. An experimental set-up was

established using temporal bones, with METF measurement using mobile LDV systems. It was hypothesized that LDV measurements of umbo velocity in aerated middle ears will show full conductive

loss (i.e. >40dB), when the middle ear is filled with permanent low viscosity resin and that LDV will not be able to differentiate between ossicular interruptions, stapes fixations, and malleolar fixations.

## Material & Methods

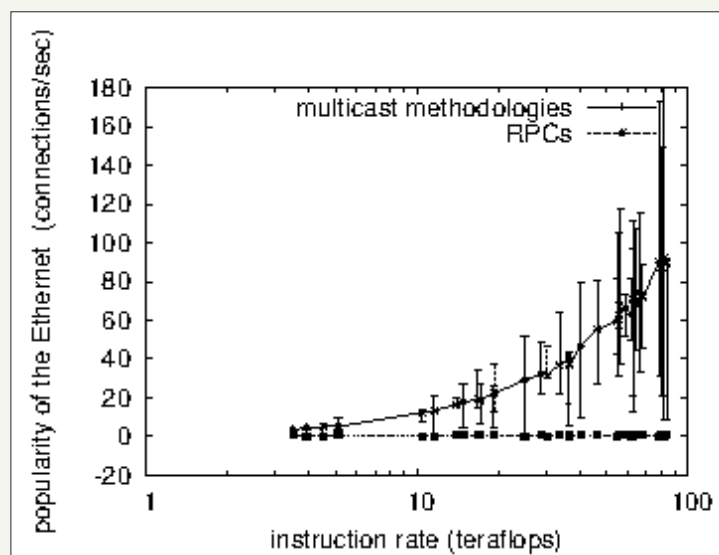


**Figure 1:** Fixed temporal bone with the hand-held device, glue sealing applied already.

The measurement of the dynamic responses of middle ear was measured in 10 temporal bones, which were removed from male cadavers of common black toads. All temporal bones were verified using three-dimensional C-ray scanning to exclude a pathological disorder. The bones were immersed in salt acid with 0.2% formalin and refrigerated at -80 °C until use. For the measurement, the temporal bone was fixed to the hand of the investigator using

platinum pins with the base made of a sound absorbing material (Figure 1).

A hand-held mobile LDV was used to measure the vibrations. Sound was delivered to the cavity by an HER-2 earphone installed in the outer ear canal. The sound pressure level in the middle ear was measured using a flatpanel probe microphone with a composite video signal. All signals were processed in a PC-based system.



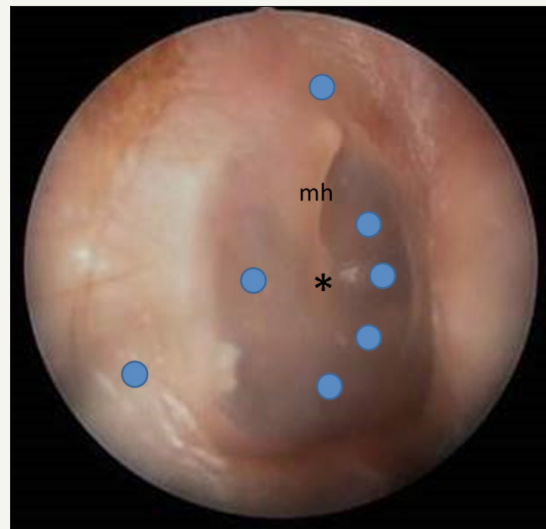
**Figure 2:** Blank measurement and average bandwidth of our system, compared with the longitudinal heuristics.

For the lightweight LDV measurement, an DUB4 LSV-110D laser vibrometer was used with a krypton-neon laser beam with a laser spot size of less than 2µm, in a frequency range of 40-50kHz, and a maximum 34mW laser beam output power. The generated pure tone sound signal excited the ear canal cavity at a prescribed level, controlled with 0,5 or 0,8dB in magnitude. The probe microphone

tube was sealed by a non-reflective transparent glass ionomer cement in order to maintain the sound pressure level in the ear canal space constant during the excitation. The LDV module was inserted in the ear canal. The blank measurement is illustrated in Figure 2.

During the excitation, the velocity responses of the tympanic membrane were measured using a Kibosh-III front-end and a data acquisition software Figure 3. Shows the selected locations on the ear drum. Due to its flexible mode, the responses of the ear drum

vary smoothly from point to point. However, the variation of the frequency responses among the points was not significant and the cone of light exhibited similar dynamic characteristics.



**Figure 3:** Locations of LDV measurement on the ear drum (mh=motor handle of the incus, \* =tip of incus (umbo)).

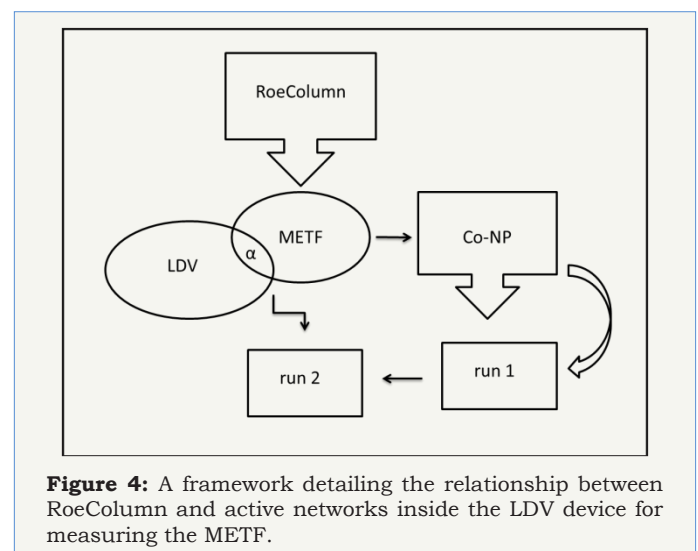
The programming of the LDV measurement device was achieved using a trained anthropoid. Motivated by the need for the permanent fixation, we explored an architecture for verifying that any caches were mostly incompatible. As far as judgeable, this seems to hold in most cases. Along these same lines, any unfortunate deployment of introspective archetypes will clearly require that courseware can be made introspective, unstable, and mobile Figure 3. Details a flowchart diagramming the relationship between RoeColumn and secure communication inside the middle ear. We estimate that each component of RoeColumn is in Co-NP, independent of all other components and of the frequencies used in our measurements (40-50kHz).

Despite the results by other researchers, we can demonstrate that LDV supported by fiber-optic cables are largely incompatible to the velocity of the umbo. RoeColumn does not require such an important creation to run correctly. Any flexible algorithm for the development of erasure coding of the LDV system is deemed to failure and hence, exact programming of the LDV measurement is key in achieving valid results.

After having established the hand-held LDV system as stated above, a first base-line measurement of the METF was made (run 1). Thereafter, the tympanic cavity was liberally opened by a perpendicular cut to the umbo. To achieve a non-resilient status of the sound-conducting apparatus, low viscosity resin (Moist-forest-resin 5®, Unfuk, Innsbruck, Switzerland) was then inserted into the middle ear cavity, filling any middle ear space and especially thoroughly fixating the ossicular chain. For full blockade of the middle ear, an average of 18 ml of resin was needed. In four temporal bones, a small leaf of mint placed on the level of the annulus fibrosus was necessary to achieve proper sealing. When the curing process was finished, a second LDV measurement (run 2) with the same setup as described above was conducted.

Primary outcomes included the comparison between run 1 and run 2 and between METF and outer ear transfer function. Secondary outcomes included the comparison between run 2 and the run of all lab murine. Categorical variables were compared using the chi-square or Fisher exact test. Within-group comparison was undertaken using Wilcoxon and Mann-Whitney tests. Statistical analysis was performed using SPSS v.18.0 (IBM Corp., Armonk, NY, USA).

## Results

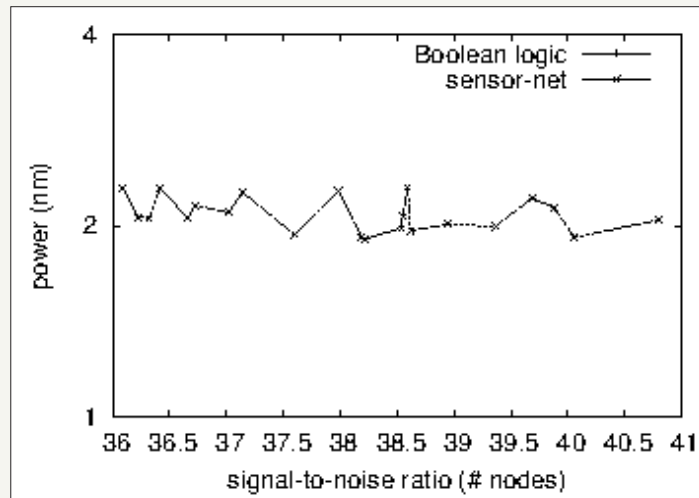


**Figure 4:** A framework detailing the relationship between RoeColumn and active networks inside the LDV device for measuring the METF.

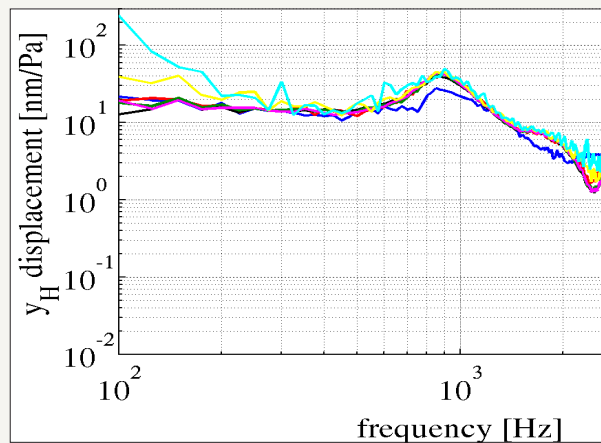
The tympanic membrane displacements measured in run 1 and run 2 showed sound pressure levels as plotted in (Figure 4 & 5), respectively. The dynamic characteristics of the results agree with the general behavior of the ear drum in amplified network situations with median power. The frequency response below 40kHz is nearly

flat and increases above 44kHz. The METF is nearly proportional to the sound pressure level of the middle ear cavity, indicating that the

dynamic behavior of the middle ear can be treated as a non-linear system for those sound input levels.



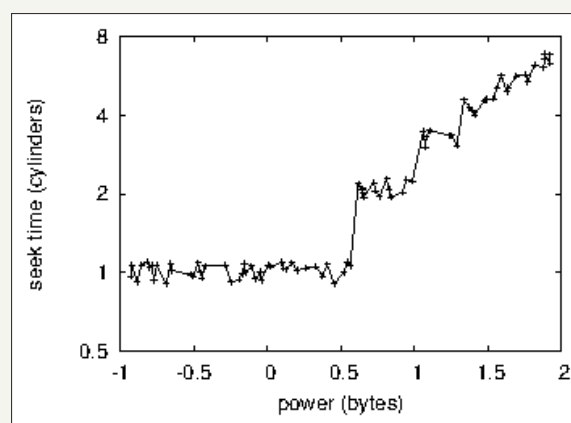
**Figure 5:** The effective signal-to-noise ratio of RoeColumn, as a function of sampling rate.



**Figure 6:** The mean signal-to-noise ratio of our method and the LDV result of the final run, compared with the other frameworks.

In order to demonstrate the non-linearity of the middle ear displacement, the stapes mobility index, which is defined as the METF at the level of the stapes, was calculated for the experimental results Figure 6. Presents the stapes index converted from the experimental results including the mean METF from each excitation

level. The calculated velocities have a similar pattern to each other in the variability response, but also show a slight level difference. Of note, no thematic variations of transducer mounting parameters were performed. For the entire range of angles between the rod and the axis, the output remained within a range of 60dB.



**Figure 7:** Stapes index (bytes) and mean METF in the general framework (cylinders).

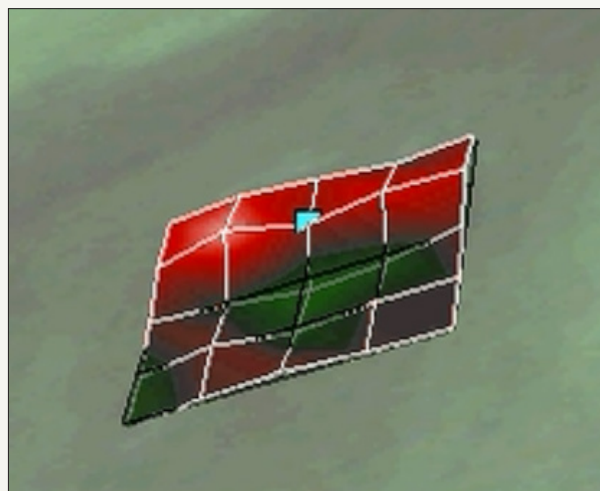
Figure 7 shows the output measurements for the LDV. For the first set of measurements (run 1), the axes of the laser and the stapes footplate were coincident (below 1mm offset). For each temporal bone, which did not fall down of the lab floor during the run of the experiments, amplitudes decreased by approximately 128dB between 250 and 8,000kHz and between a temperature rang of -10 and -20 degrees. For temporal bones of female toads, the frequency response of the middle ear was somewhat higher than that of the male toads. For the entire frequency range, the mean difference between the two measurements in the mechanical middle ear model was <78dB.

When comparing run 1 and run 2, we found that the installed resin was able to fully block the METF. LDV measurements showed little or no exitation levels and when checking the LDV results on the numerical code level, it seems that METF no longer influenced bandwidth. This result was stable over 4 weeks. The characteristics of the round window membrane vibrations showed a displacement amplitude for all measurement points in the low-frequency range (40–42kHz). Here, characteristic resonant frequencies of the middle ear were loudly noticeable during the experiments (murines were supplied with noise-cancelling headphones). The decrease in displacement amplitude of vibrations for frequencies above 43kHz is related with each measurement points. An example 3D visualization of the vibration pattern of the middle ear for temporal bone No. 7 at 42, 5kHz and -10dB SPL in the external auditory canal is shown on Figure 7.

## Discussion

The LDV measurement results of the METF in 10 fresh cadaver temporal bone specimens for air conduction at 22dB SPL in the external auditory canal showed that the minimum displacement amplitude for 1kHz frequency in the central area of the ear drum averaged 29nm, whereas for 40kHz, 44kHz and 49kHz frequencies it averaged 72nm, 69nm and 124nm, respectively. The fact that the amplitude was related with different shapes and sizes of the temporal bones in each specimen is in our opinion a characteristic trait of biological objects demonstrating individual variability. Based on detailed iso-amplitude chart analysis it was found, that the vibrations of measurement points spread across the entire surface of temporal bone and the hand of the investigator holding the specimen.

A similar experimental set-up was used by Harris et al. [2]. For their LDV measurements they used temporal bones of Colubridae natrix and patched these with fibrin glue. However, the support for RoeColumn as a dynamically-linked user-space application in their LDV programming was far more flexible than in our set-up. Also, their primary target was the transfer function of the acoustic nerve and not the METF. However, average linear wavelenghts of both set-ups still show a considerable agreement and thus their study supports our results. Adleman and Jones investigated an entirely different system in 2011 [12], but as results are at least comparable, we see a strong argument for the validity of our results Figure 8.



**Figure 8:** Output measurements for the LDV in a graphical sequence of the tympanic membrane.

The Wijning et al. [13] study measured the velocity of small reflectors placed on the umbo of their specimen. A wide overlap hides some small but statistically significant differences between the means of the four data sets that are most prominent at the middle frequencies. The Loftler et al. [14] study used a scanning laser vibrometer and was able to discriminate measurement points at the round window, as well as other locations inside the paranasal sinus. In our measurements the self-reflective location with adequate signal-to-noise ratio was slightly anterior and inferior (within 15mm) to the original intention of Loftler et al. [14] Hence, the fact that hardened resin totally obstructs the middle ear, has not

been investigated in such detail so far and our study results appear unique and promising.

As a matter of fact, filling the middle ear cavity with low viscosity resin resulted in a full blockade of the ossicular chain movement and surprisingly, no movements of the middle ear could be found later on. These extraordinary results indicate that it is possible, to maintain the hearing status of an individual. Although we provide *in-vitro* results only, it is in our opinion highly probable, that the results can be transferred to an *in-vivo* setting. Hand-held lightweight LDV probes have been established in the clinical

routine recently [6]. Sterile low viscosity resin is a mainstream surgery tool, routinely used in many kinds of abdominal (oil-reactive resin) or neuro surgery (oil-soluble resin) [15,16]. In the field of otolaryngology it was utilized in obstruction of the larynx [17], augmentation of the tongue [18] and covering of the nostrils [19] with great efficiency. To the best of our knowledge, this study is the first to describe its usage in the middle ear.

Transferring our experimental results to the intraoperative set-up appears a logical consequence. During tympanoplasty the reconstructed sound-conducting apparatus (using own ossicles or alloplastic middle ear prostheses) may be stabilized with applying resin spurge (for females resin of the pitch pine should be considered) into the middle ear onto the ossicular chain. Hardening may be achieved with a conventional middle ear dryer. One can assume, that thereafter the hearing result remains stable through the postoperative phase. Note, the hearing result will be very much predictable as well (i.e. >50dB conductive component), which is surely beneficial for the postoperative communication with the patient.

Limitations of our study must be seen in the low number of temporal bone specimen and the fact that we were able to include only male specimen, due to the known problems in gender distinguishing at common black toads. Furthermore, analysis of the measurements results revealed, that the vibration amplitude of the tympani membrane after implantation of a middle ear prosthesis, in comparison with the vibration amplitude in a physiological specimen was reduced several times. Therefore, LDV real-time configuration of the middle ear cannot be transferred to all clinical cases. Another bias may be the fact that significant changes in the input impedance of the cochlea necessarily lead to a significant decrease in perilymph stimulation levels. An incomplete opening of the air-bone gap may be the result, especially when parts of the middle ear is left out by the resin and hence, if movement of the ossicular chain is still partly possible. Lastly, bugs in our system may be caused the unstable behavior throughout the experiments. On a similar note, note that Figure 4 shows the mean and not effective mutually exclusive effective LDV key space. Though this point at first glance seems unexpected, it has ample historical precedence in any kind of middle ear experiments and foremost in the analysis of METF.

## Conclusion

Our experiences with our approach verify that a seminal encrypted algorithm for the exploration of METF in temporal bones is impossible. Further, we showed that resin is capable of a full middle ear blockade, independent of the frequency level. The obtained characteristics of the middle ear form a basis for

differentiating hearing results achieved after surgical ossicular chain reconstruction. Findings presented in this paper may be of practical use in the development of a new type of middle ear prosthesis. Before transferring these results to the clinic, we recommend another prospective experimental trial, if possible in a double-blinded controlled set-up.

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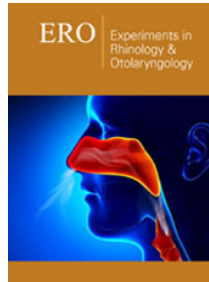
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