Chapter 12
Characterization of the Human Eardrum Transfer Functions Under Moderate and High-Intensity Sound Levels by High-Speed 3D-DIC

Jonathan Oliveira Luiz, John Rosowski, Yoshiaki Inuzuka, Cosme Furlong, and Jeffrey Cheng

Abstract Characterizing the damage mechanics of the human middle ear under different acoustic excitation levels is still under investigation. Limited research exists on the non-linear behavior of the human tympanic membrane (TM), commonly known as the eardrum. Specifically, when it's exposed to high-intensity sounds (i.e., >130 dB SPL), such as loud music and blasts, despite its accepted linear mechanics under lower sound pressures (i.e., <120 dB SPL) typical of everyday environments. Our research aims to characterize the transition of TM responses from linear to non-linear behaviors with increasing sound levels, identifying sound thresholds at which non-linear behaviors emerge. The methodology under development integrates High-Speed Three-Dimensional Digital Image Correlation (HS 3D-DIC), optimized for small field-of-view (FOV), within a custom-built acoustic system. It uses a loudspeaker to generate moderate-level impulsive sounds (100–160 dB SPL) and a shock tube to produce high-intensity blasts (150–180 dB SPL), enabling a TM response evaluation across a wide range of impulsive sound levels. Using two high-speed cameras at up to 100,000 frames per second, HS 3D-DIC captures TM motions ranging from sub-micrometer to millimeter scales, while high-speed pressure sensors characterize pressure profiles near the TM. Moreover, sample preparation effects are assessed. Transfer functions (TFs) for over 60,000 points on the TM surface are computed by normalizing displacements with sound pressures using Fourier analysis, facilitating comparisons of TM mode shapes at different pressure levels. Initial results reveal linear TM TFs at moderate levels consistent with literature, while non-linear TM TFs at high intensities are still under investigation. This work is expected to enhance knowledge of TM mechanics at different levels and assist in the development of grafting materials and methods to repair the TM.

Keywords Tympanic membrane · Acoustical Transfer Functions · Nonlinearity · High-speed 3D-DIC · Shock tube · Ear injury

Introduction

The human middle ear is an air-filled cavity that includes the eardrum (tympanic membrane, TM) and three tiny bones known as ossicles (malleus, incus, stapes). The TM generates complex, highly frequency-dependent, and multifaceted patterns of vibrations when sound waves hit it [1, 2, 3]. The ossicles couple the resulting sound energy from the TM to the inner ear,

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where sensory hair cells stimulate nerve signals to the brain. The middle ear transfer function (TF) describes how sound pressure at the TM is transformed into motion at a downstream location, such as the stapes or umbo, characterizing the frequency-dependent input-output relationship. This function quantifies how the middle ear amplifies, attenuates, or phase-shifts sound energy across different frequencies, providing insight into normal and pathological hearing function [4].

It is well accepted that at low to moderate levels ($<\sim$120 dB SPL), the middle ear operates linearly, with resulting displacements ranging in the nanometer to micrometer range [5]. This means the input exerted into the TM (sound pressure) is proportional to the output (motions). This way, for transfer functions computed in the linear range, in which motions are normalized by pressure, it is expected that results are always consistent. At higher sound levels (above $\sim$120 dB SPL), however, the displacements grow to the micrometer to millimeter range [1], and nonlinearities emerge, altering the resulting transfer functions. The exact threshold at which nonlinear behavior begins and the mechanisms driving these nonlinearities remain unclear, hindering accurate middle ear models, TM repair methods, and effective hearing protection design [5].

Nonlinearities arise when the relationship between input and output variables, such as force and displacement, deviates from proportionality. They can be broadly classified into geometric and material nonlinearities. Geometric nonlinearity occurs when large deformations significantly alter the structure's shape, causing stiffness to become a function of displacement. This effect becomes relevant when strain exceeds typical thresholds, around 5%, leading to changes in structural behavior [6]. Material nonlinearity, on the other hand, occurs when a material's stress-strain relationship is not constant, often due to viscoelasticity, plasticity, or hyperelasticity [7]. Many biological and engineering materials exhibit both types of nonlinearities, affecting system behavior under varying loads and excitation conditions. Accounting for these effects improves the accuracy of models describing mechanical responses in complex structures, such as the middle ear.

In this work, we compare the behavior of the human TM at moderate (linear response) and high-intensity (nonlinear response) sound levels. We aim to investigate how the TM's vibration response changes as sound pressure increases, focusing on the onset and progression of nonlinearities. Examining middle ear nonlinearities requires assessing both geometrical and mechanical nonlinearities, as well as rate-dependent behaviors, across varying sound levels and excitation rates. Nonlinearities in the middle ear have been investigated in both animal models and humans [8, 9]. However, further clarification is needed for the human middle ear, especially nonlinearities across different sound levels using full-field techniques to describe the TM complex behavior and determine the nonlinearity threshold more accurately.

By applying a methodology that uses a validated integrated system, we capture the complex motion of the tympanic membrane across various sound levels and excitation rates. Through Fourier analysis, we compute the corresponding transfer functions for different conditions and compare the differences for varying excitations. Initial results give new insights into middle ear nonlinear behavior and will be used for future evaluation and analysis.

Methods

In this study, we present a methodology specifically developed to investigate nonlinearities in the human middle ear [1, 10]. The integrated experimental setup allows for two excitation sources: a loudspeaker generating acoustic clicks for low-to-moderate impulse-like pressure waveforms and a pressure-adjustable, fully characterized, repeatable shock tube producing blast waves for high-intensity sound levels [1, 10, 11]. These sources are synchronized with high-speed measurement techniques.

To capture the complex full-field response of the tympanic membrane (TM), high-speed 3D Digital Image Correlation (3D-DIC) provides full-field 3D motion data across the entire TM. A differential Laser Doppler Vibrometer (LDV) is used for two purposes: 1) validating DIC measurements and 2) measuring specific points of interest in the middle ear (e.g., umbo or stapes). The high-density data from DIC enables a detailed analysis of TM kinetics and kinematics. Additionally, a high-speed Schlieren imaging system visualizes the fluid-solid interaction between the temporal bone and the shock wave [12]. High-frequency pressure sensors measure the pressure near the sample, completing pressure characterization. A representation of the integrated system is shown in Fig. 1. An insert, shown in Fig. 1 b, details the temporal bone (a complex bone within the skull base that contains, between other structures, the middle ear) prepared for an experiment.

The application of 3D-DIC in this context presents several challenges: (1) a small field of view (FOV), as the human tympanic membrane is only $\sim$9 mm in diameter; (2) a long working distance, since high-speed cameras must be positioned away from the shock tube to prevent damage; (3) the need for high-speed measurements to accurately capture rapid TM motion; and (4) minimal sample preparation, as the TM is a thin membrane ($<150\ \mu$m), and a heavy paint layer would alter its natural response. Challenges 1, 2, and 3 are addressed using specialized equipment, including high-magnification lenses and high-speed cameras, enabling measurement speeds up to 100k FPS. This system was previously tested and validated [1, 11, 12, 13]. Given the specialized nature of this 3D-DIC application, we validated our measurements under two conditions: moderate sound levels and high-intensity pressure levels. Full-field 3D-DIC data were compared against

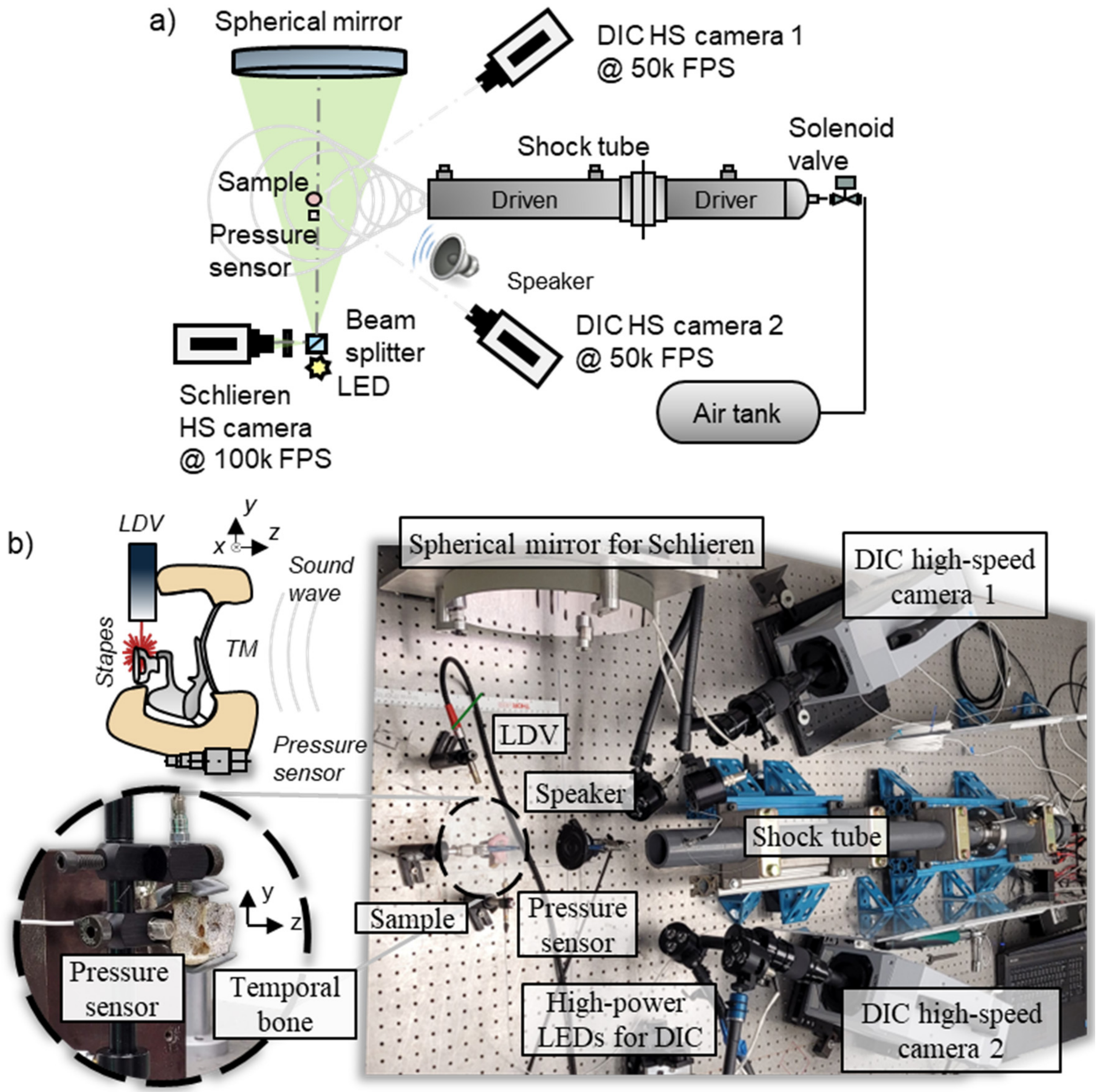

Fig. 1 a) Schematics of the integrated experimental setup; b) Realization of the integrated system with an inset of a cadaveric temporal bone under test.

LDV measurements at the center of a 10 mm artificial membrane to assess accuracy, as depicted in Fig. 2. Despite the event lasting only a few milliseconds, 3D-DIC and LDV measurements for both click and blast exposures showed an average error of less than 1%, confirming the accuracy of 3D-DIC at moderate and high-intensity levels.

To assess challenge number 4, the effects of painting on thin membranes with responses similar to the human TM were addressed. Tunable thin membranes capable of maintaining a consistent response were designed and fabricated, as shown in Fig. 3 a. These membranes are made of latex, with a diameter of 10 mm and a thickness of $\sim$100 μm. The painting process involved using an airbrush to apply different coatings to the artificial sample. The response to acoustic excitation was compared before and after painting to determine if the response remained unchanged. For this, transfer functions at the center of the sample were computed using an LDV. Various coating materials were tested, as shown in Fig. 3 a. Typically, for DIC painting, a white background is first applied, followed by black speckles to achieve better contrast [14]. In this study, however, we tested a less conventional method: only white speckles were applied to minimize the added mass to the

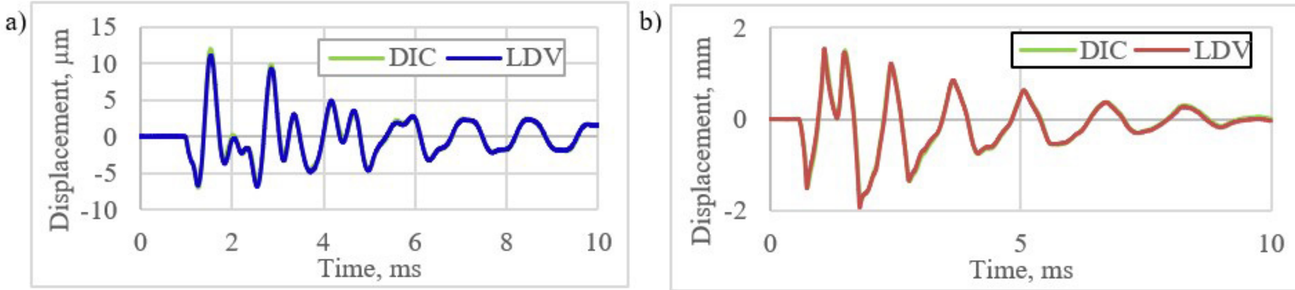

Fig. 2 Validation at two pressure levels: a) Acoustic click, ∼35 Pa (125 dB SPL); b) Blast exposure, 20 kPa (180 dB SPL).

sample and avoid altering the membrane stiffness, which could be caused by a uniform background paint, thus reducing any potential impacts the coating could have on the thin membrane's natural response.

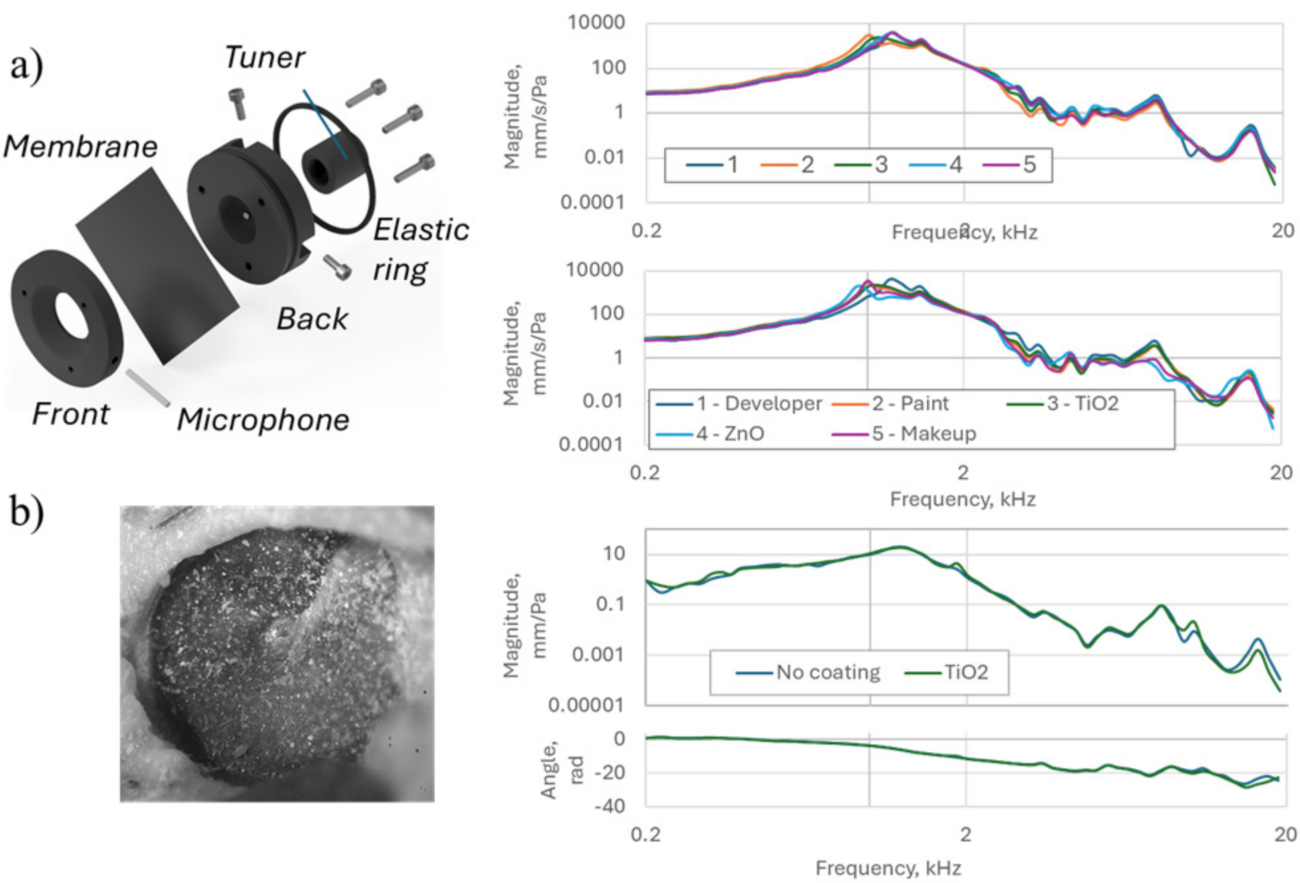

Fig. 3 Painting evaluation: a) Tunable thin membrane with bracket designed for consistent response; b) Test on a real TM with TiO_2 speckles.

The coating that yielded the best results, TiO2 speckles, was applied to a real TM, as shown in Fig. 3 b. TF measurements taken at the umbo, before and after sample preparation, show no significant change in the tympanic membrane's response, confirming that the sample preparation method does not alter its characteristics. Additionally, TiO2 speckles were successfully tracked by the 3D-DIC algorithm while maintaining a minimally invasive preparation. All DIC computations in this work were performed using VIC-3D software from Correlated Solutions [15].

In a previous study, we were unable to compute TFs for blast experiments due to issues such as pressure sampling acquisition and vortex rings, which caused pressure waveforms to deviate from an impulse-like response [1]. In this work, we adopted a sampling rate of 200 kHz for pressure acquisition and eliminated vortex rings by positioning the shock tube off-axis, as shown in Fig. 4. While the primary shock wave remains spherical and interacts with the sample regardless of the shock tube's alignment with the specimen, the vortex ring travels along the shock tube's longitudinal axis, preventing interaction with the tested temporal bone.

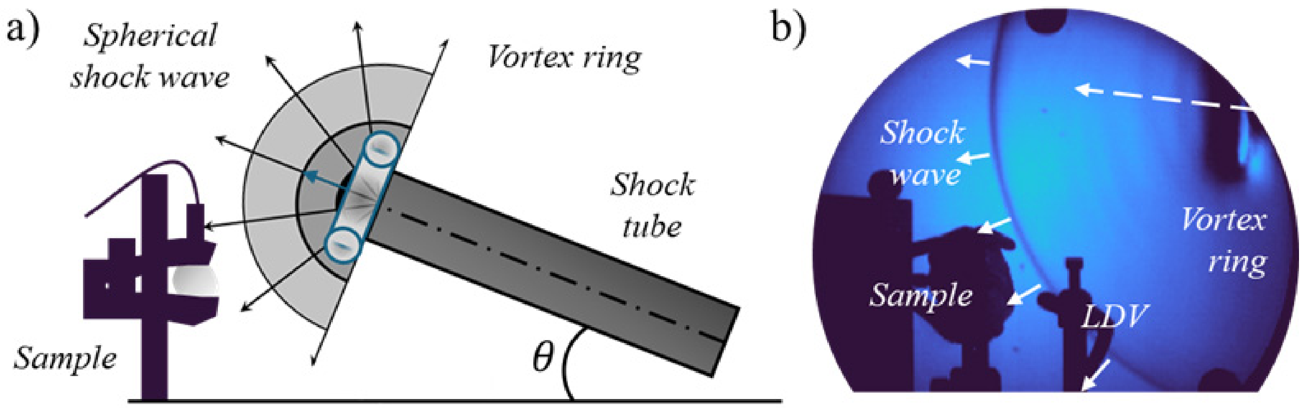

Fig. 4 Impulse-like blast exposure: a) Representation of shock tube off-axis configuration; b) Schlieren image showing fluid-solid interaction between shock wave and temporal bone, while vortex ring deviates from the tested sample.

The tested samples consist of cadaveric human temporal bones, carefully prepared for these experiments. Transfer functions for different excitation levels across the entire surface of the TM were computed using the equation

$$TF\left(x,y,f\right)=\frac{FFT\left(w\left(x,y,t\right)\right)}{FFT\left(p(t)\right)}, \tag{1}$$

where FFT represents a fast Fourier transform, w is displacement along z-direction, and p is the pressure measured near the sample. Additionally, impulse responses (IRs) are computed by

$$IR\left(x,y,t\right)=IFFT\left(TF\left(x,y,f\right)\right). \tag{2}$$

Finally, as an additional method to assess potential nonlinearities, we compute the ratio of volume displacement and pressure energy flux accumulated over time, as in

$$Ratio\left(t\right)=\frac{E^{*}}{V}=\frac{\frac{1}{\rho c}\int_{0}^{T}p^{2}\left(t\right)dt}{\int_{0}^{T}\int_{a}^{b}\int_{c}^{d}w\left(x,y\right)dydxdt}. \tag{3}$$

Results

As a representative result, we present time-domain measurements of the tympanic membrane (TM) using high-speed 3D-DIC at two excitation levels: an acoustic click (2000 Pa, 160 dB SPL) in Fig. 5 a and a blast (15 kPa, 177.5 dB SPL) in Fig. 5 b. Displacement data are shown along the z-direction at three points of interest (POIs), illustrating the TM's response under both loading conditions. The click is expected to be closer to the linear range of the TM, while the blast falls within the nonlinear regime. Specific instances are highlighted to demonstrate key deformation behaviors, with detailed motion decomposition at time instance t_3, as shown in Fig. 5 c and Fig. 5 d.

The data shown in Fig. 5 is used to compute the transfer function, following Eq. 1. The results are presented in Fig. 6. For the identified dominant frequencies, the corresponding mode shapes are computed at both moderate and high-intensity sound levels. The reduced magnitude and altered shape of the blast-induced transfer functions indicate a significant frequency-dependent compressive nonlinearity.

Impulse responses characterize the time-domain behavior of the TM by describing its motion following a brief acoustic stimulus. They provide insights into how the TM and connected structures respond over time, revealing details about damping, resonance, and energy transmission in both normal and pathological conditions. The corresponding impulse responses were computed using Eq. 2, with the results shown in Fig. 7. Key features of the impulse responses are examined to identify

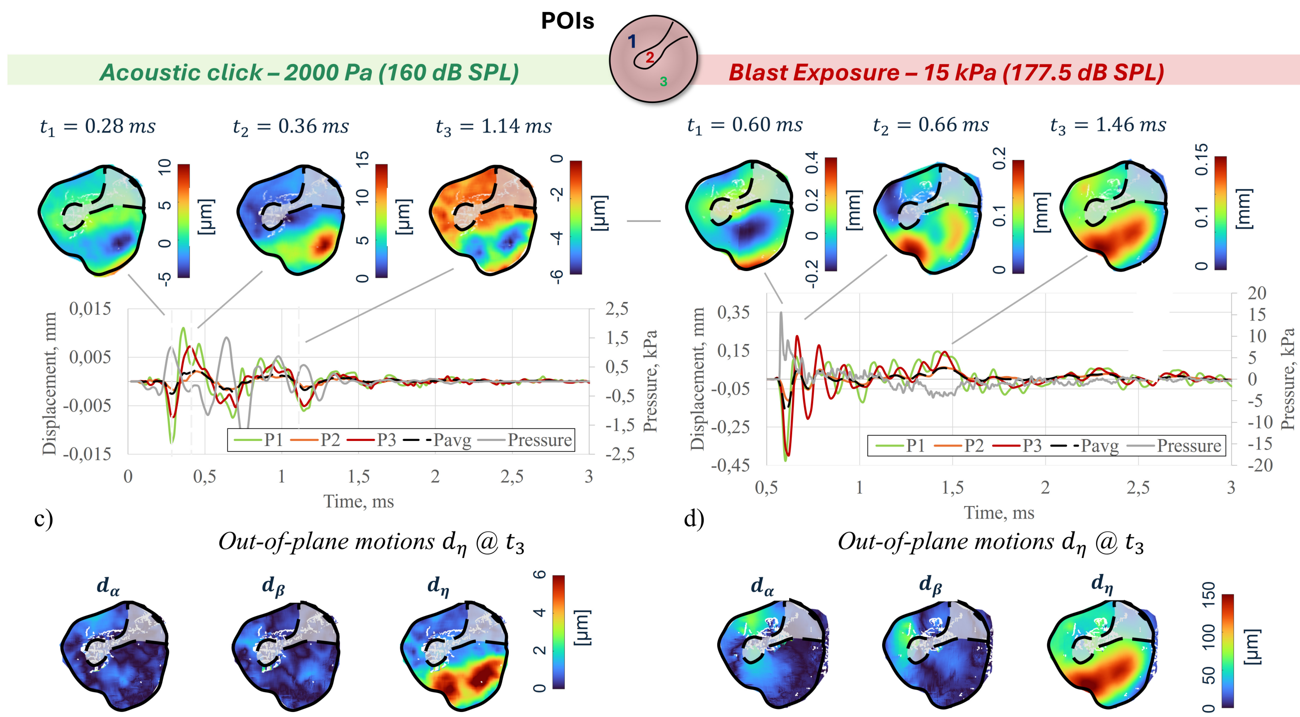

Fig. 5 Time-domain measurement of a temporal bone exposed to: a) Acoustical click (50 Pa, 128 dB SPL); b) Blast (15 kPa, 177.5 dB SPL). c) and d) show motion decomposition for the corresponding time instances at t_3.

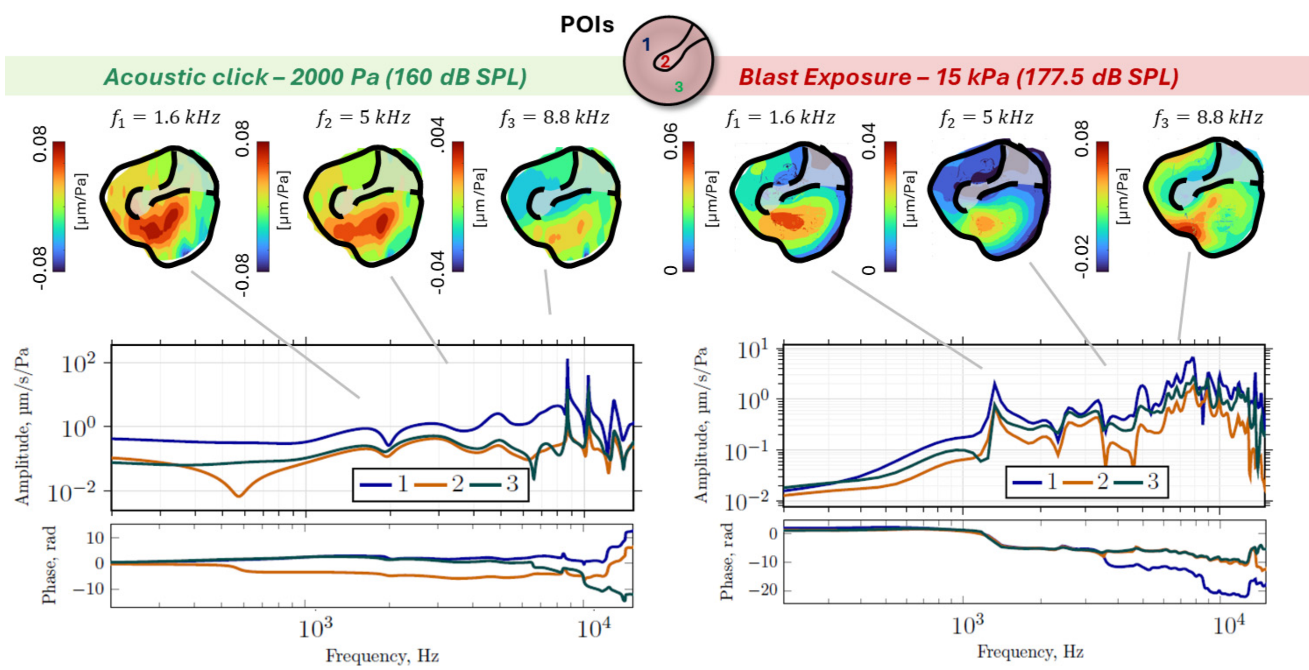

Fig. 6 Transfer functions computed for: a) Acoustical click (2000 Pa, 160 dB SPL); b) Blast (15 kPa, 177.5 dB SPL).

spatial variations across the TM. At high-intensity levels, the reduced magnitude and altered motion patterns further suggest a compressive nonlinearity.

The ratio of volume displacement to pressure energy flux assesses how efficiently acoustic energy is converted into TM motion. Since pressure energy flux represents the input energy and displaced volume reflects the TM's response, discrep-

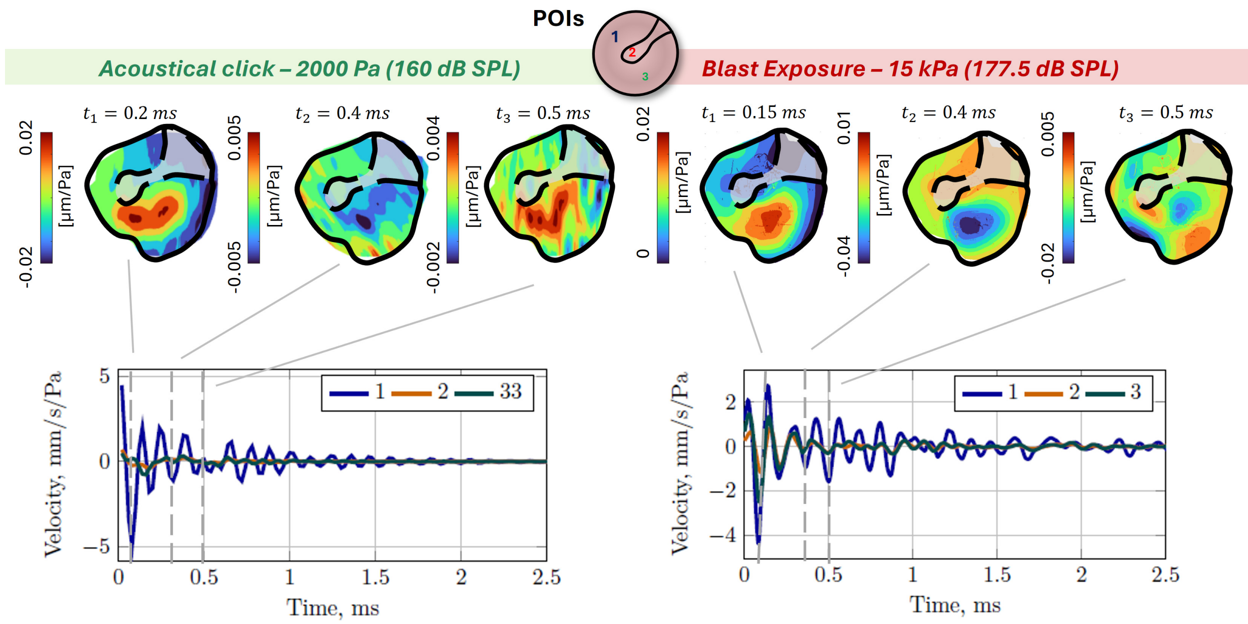

Fig. 7 Impulse responses computed for: a) Acoustical click (2000 Pa, 160 dB SPL); b) Blast (15 kPa, 177.5 dB SPL).

ancies at higher intensities provide further evidence of nonlinearities in the middle ear. Comparing displaced volume and pressure energy flux reveals both kinematic and kinetic effects, offering insight into nonlinearities and energy transfer variations across sound levels. This ratio is calculated for the same cases shown in Fig. 5 using Eq. 3 and is presented in Fig. 8. Deviations from a consistent ratio at moderate and high intensities indicate nonlinear behavior, with the slower growth of Volume/Pressure further suggesting some level of compressive nonlinearity.

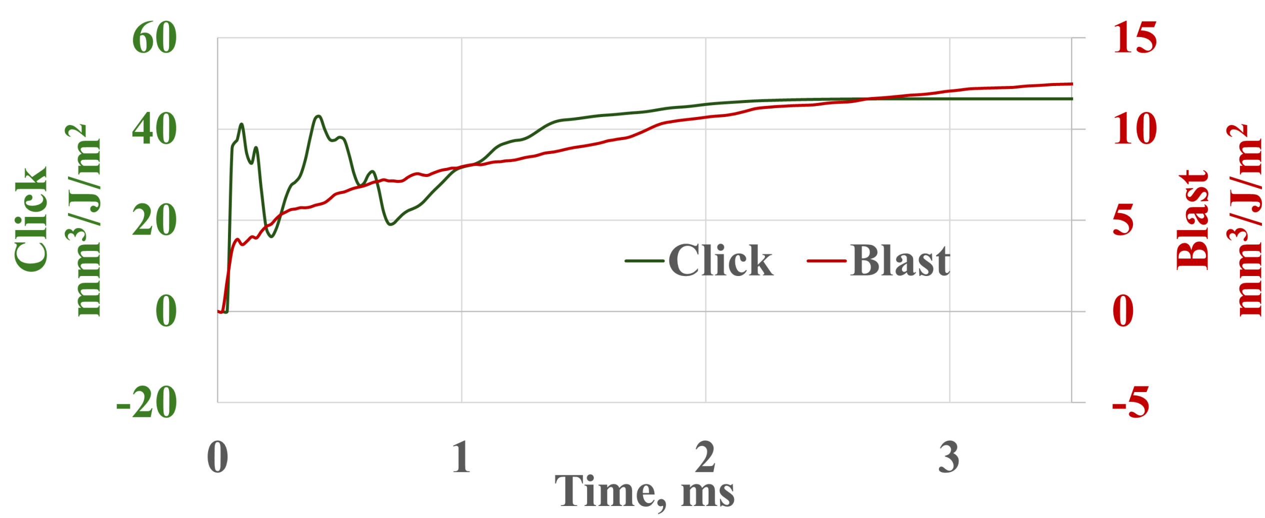

Fig. 8 Volume displacement vs. Pressure energy flux.

Conclusion and Future Work

This study demonstrates the capability of high-speed 3D-DIC to provide detailed spatial and temporal characterization of TM motion at moderate to intense excitation levels, surpassing traditional single-point measurement techniques. The initial results indicate that the middle ear exhibits some level of compressive nonlinearity at high-intensity sound levels, with

TM displacement growing more slowly than pressure increases. Changes in transfer functions, mode shapes, and impulse responses suggest the presence of both geometrical and mechanical nonlinearities.

To further validate these findings, additional samples and excitation levels are needed to confirm observed trends and enhance statistical significance. Future work will focus on expanding the dataset and applying data mining and machine learning models to extract deeper insights into middle ear mechanics. These efforts aim to improve hearing protection design and diagnostic methods. Additionally, the minimal sample preparation required for 3D-DIC measurements suggests potential for in vivo applications, which could enable direct assessments in patients and further advance clinical and research capabilities in auditory science.

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