Real-Time Measurement of Basilar Membrane's Transient Response to Blast Overpressure

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ABSTRACT

Blast overpressure (BOP) is a major cause of auditory injury in military personnel, yet the relationship between BOP intensity and cochlear basilar membrane (BM) motion under high-intensity blast loading remains poorly understood. This study experimentally quantified basal and middle turn BM responses to high BOP levels ranging from 26 to 64 kPa (182–190 dB) using human cadaveric temporal bones (TBs). A dual laser Doppler vibrometry system simultaneously measured BM motion and TB movement, while synchronized pressure sensors recorded incident and ear-canal pressures. As BOP increased, peak-to-peak BM velocity increased from 200 to 1300 µm/ms in the basal turn and from 240 to 490 µm/ms in the middle turn. Correspondingly, peak-to-peak BM displacement increased from 30 to 310 µm and from 82 to 299 µm in the basal and middle turns, respectively. Directional BM velocities exhibited consistent pressure-dependent trends and high waveform repeatability across tests. These findings provide the first high-resolution characterization of BM movement under high intensity BOPs and offer important insights into mechanisms of blast-induced auditory injury and protective device development.

INTRODUCTION

BOP exposure is a leading cause of auditory injury among military personnel, often resulting in temporary or permanent hearing loss. While previous studies have investigated middle ear responses to blast loading, the mechanical behavior of the cochlear BM under high-intensity blast conditions remains largely unexplored. Excessive BM motion is believed to contribute to structural damage within the organ of Corti, including hair cell injury and disruption of sensory transduction. However, experimental data directly linking BOP magnitude to BM dynamics are limited due to technical challenges in measuring intracochlear motion during blast events. This study aims to quantitatively characterize BM motion in response to controlled BOP exposures using human cadaveric temporal bones and high-speed laser Doppler vibrometer.

METHODS

1. Fifteen fresh human cadaveric TBs were included in this study, with measurements obtained from the basal turn (n = 8) and middle turn (n = 7). The cochlea was surgically accessed through the scala tympani (ST).
2. Reflective microbeads were applied to the BM surface to enable laser LDV signal acquisition for motion tracking and sealed with a glass coverslip to preserve cochlear fluid integrity and mechanical boundary conditions.
3. BOP was generated in an anechoic chamber and measured using two pressure sensors positioned outside the ear canal (P0) and inside the ear canal near the tympanic membrane (P1).
4. A dual LDV system simultaneously measured TB motion (reference) and BM motion to obtain the true intracochlear displacement.
5. All pressure and vibration signals were synchronized and recorded at a sampling rate of 1 MHz for high temporal resolution analysis.

RESULTS

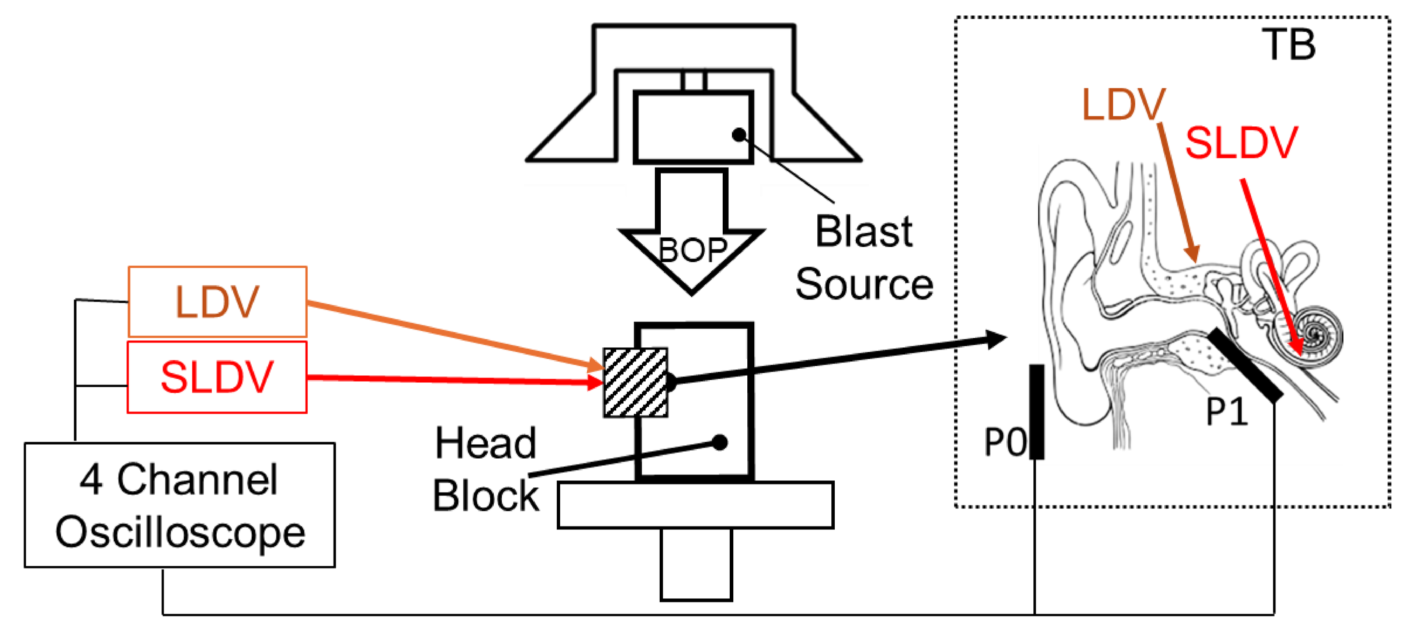

Fig. 1. Experimental Setup: Schematic of the BOP exposure and measurement system. LDV and SLDV track TB and BM motion.

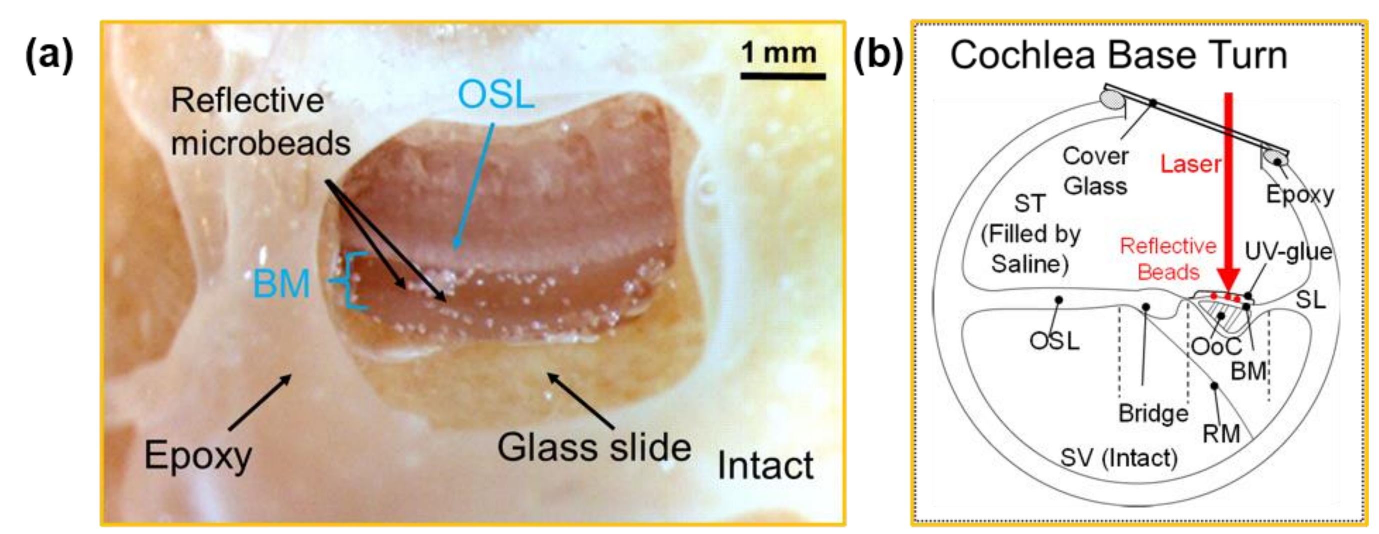

Fig. 2. (a) Surgical opening window at the basal turn of the cochlea showing reflective microbeads applied on the BM. (b) Schematic illustration of the experimental setup highlighting laser measurement, reflective beads, and UV-glue attachment.

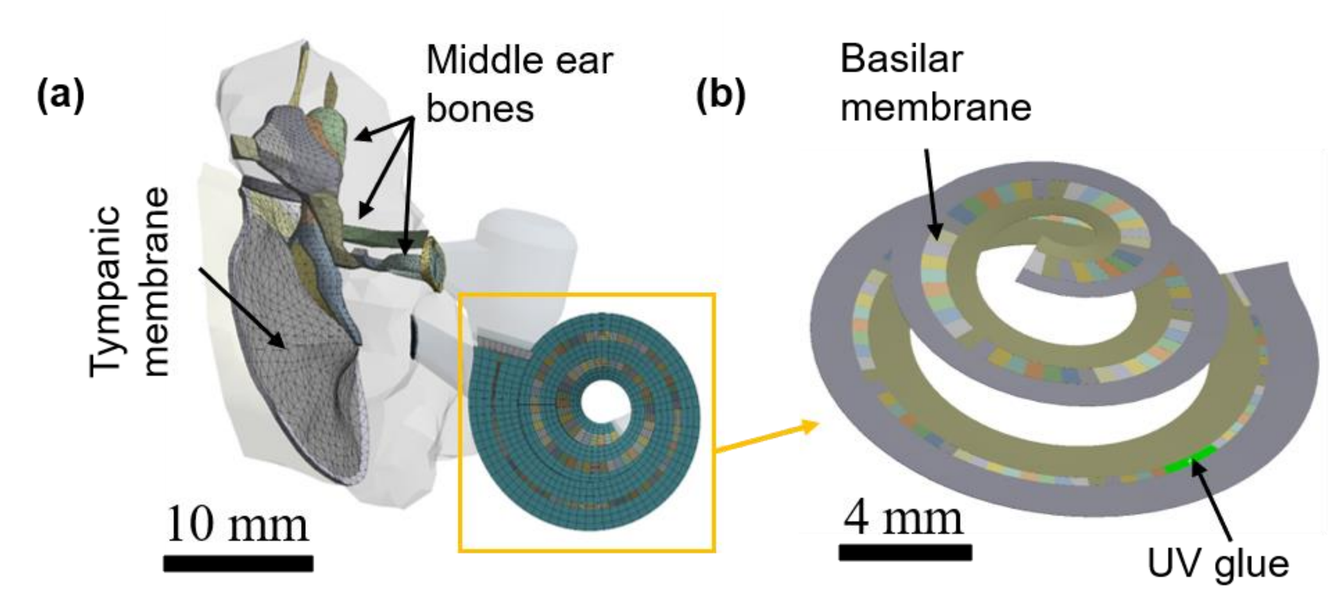

Fig. 3. (a) Three-dimensional finite element model of the human ear. (b) Enlarged cochlear model highlighting the UV-curable glue region (green).

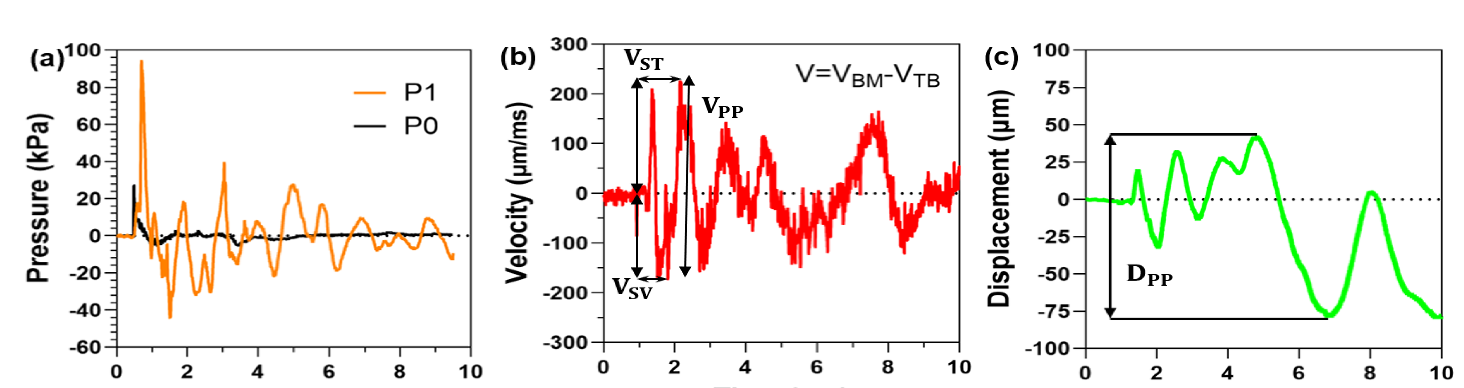

Fig. 4. Experimental results of TB 24-4: (a) pressure measurements; (b) Velocity of BM obtained by subtracting LDV from SLDV;(c) displacement measurements.

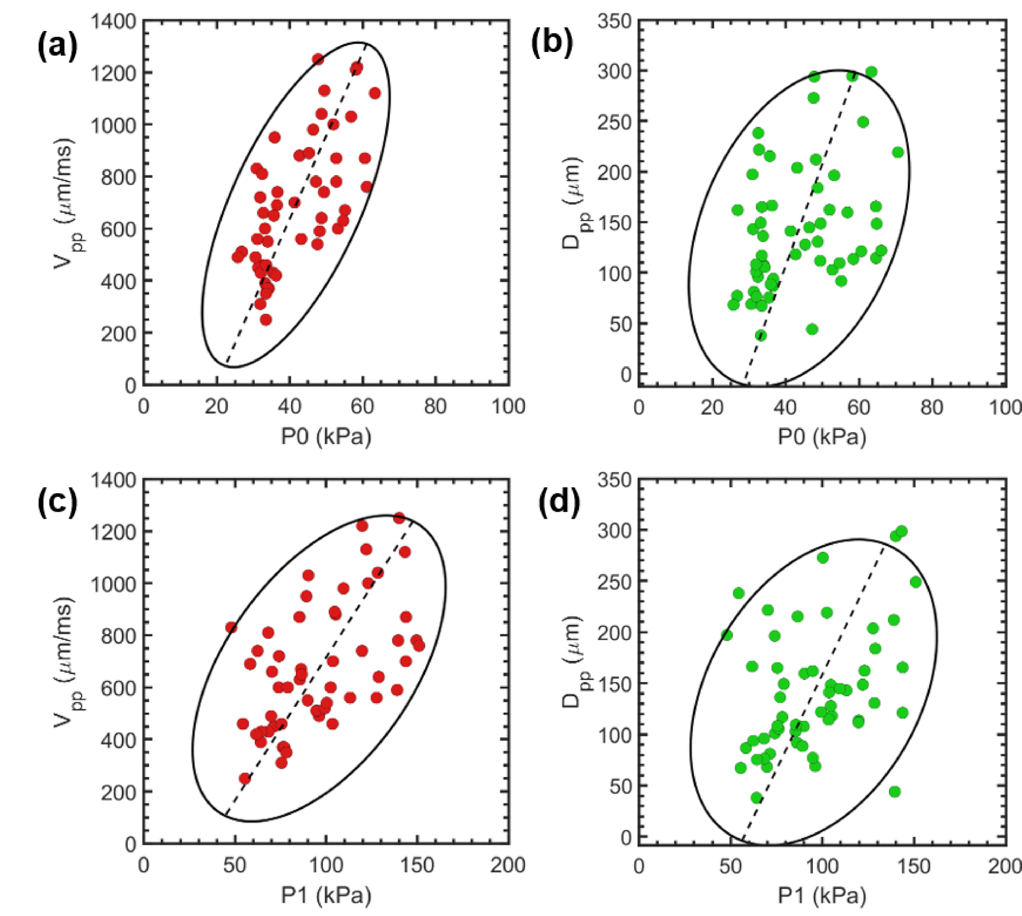

Fig. 5. Pressure–BM motion relationships. (A,B) V_{pp} versus P0 and P1; (C,D) D_{pp} versus P0 and P1. Solid ellipses indicate 95% covariance regions and dashed lines denote principal major axes

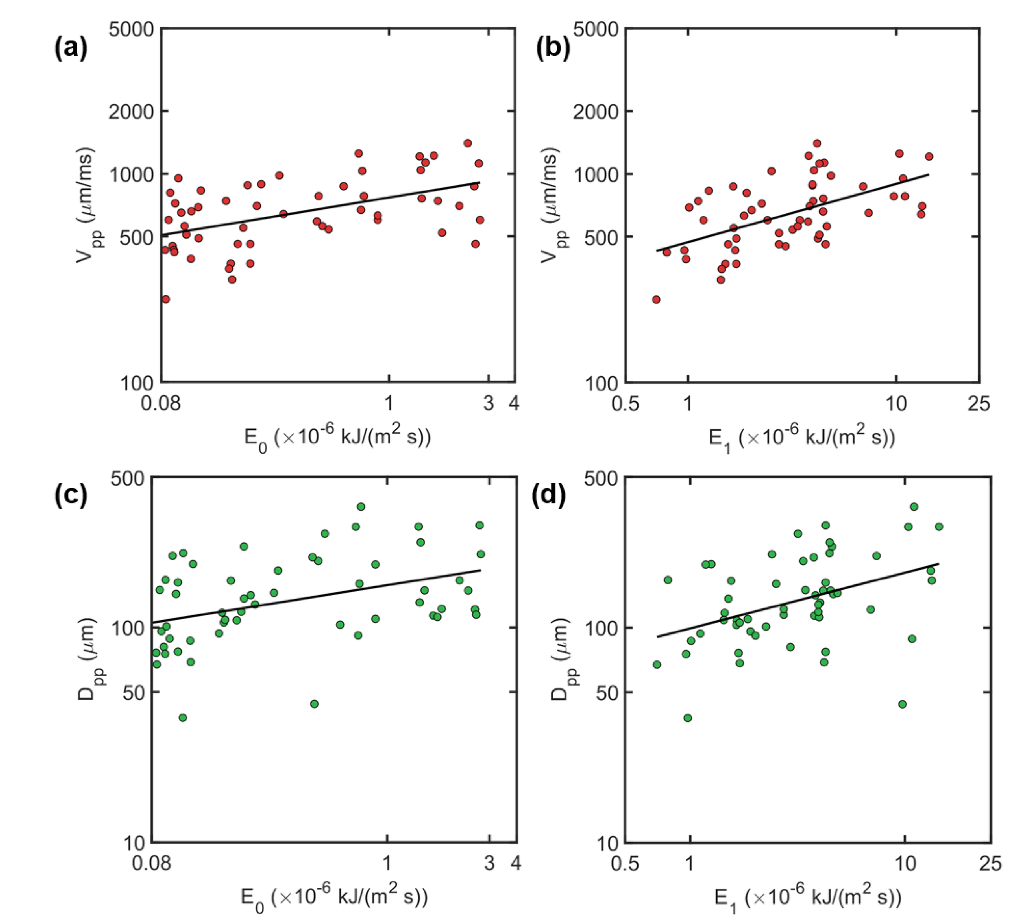

Fig. 6. Power-law scaling of basilar membrane motion with energy flux. (A,B) V_{pp} versus E_0 and E_1; (C,D) D_{pp} versus E_0 and E_1. Markers represent experimental data and solid lines indicate fitted power-law relationships.

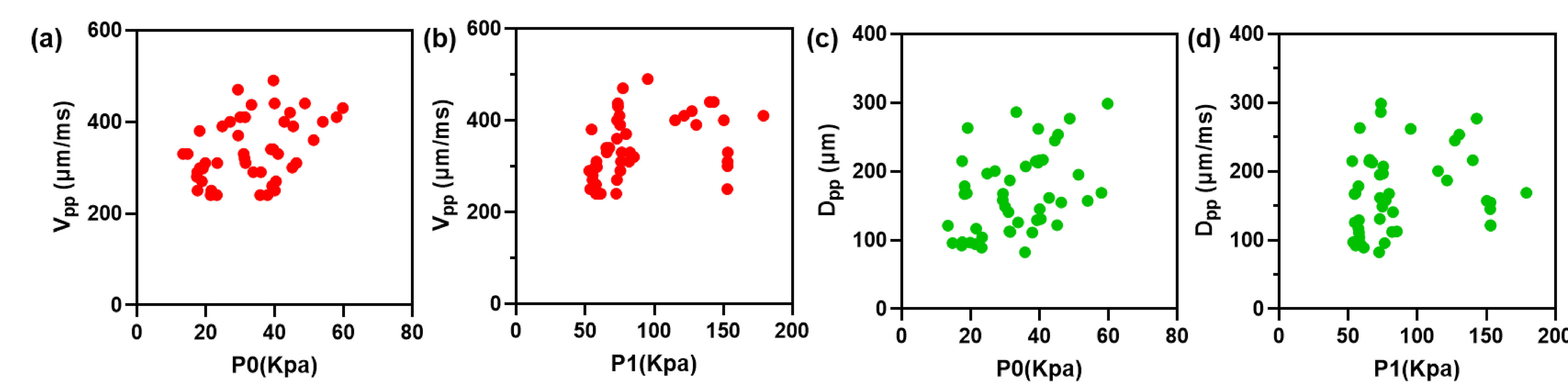

Fig. 7. Distribution of BM motion measurements at the middle turn. Peak-to-peak velocity (V_{pp}) measured at (a) P0 and (b) P1, and peak-to-peak displacement (D_{pp}) measured at (c) P0 and (d) P1. Each point represents an individual measurement from the middle-turn basilar membrane.

CONCLUSIONS

BM motion at basal turn increased with BOP intensity, indicating a strong cochlear mechanical response, with major-axis RMS deviations of approximately 7.77 – 23.74 µm/ms for velocity and 11–25 µm for displacement. Energy-based analysis revealed a power-law relationship between BM motion and pressure-derived energy flux, with scaling exponents ranging from 0.160 to 0.279. However, middle turn BM motion exhibited high nonlinear behaviors and required more experimental data like cochlear pressure for further analysis. These findings highlight the mechanical impact of BOP on the cochlea and provide a foundation for improved prediction of blast-induced hearing injury and the design of protective strategies.

References

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