A Hybrid FEM and Experimental Study on the Relation Between Temporal Bone 3D Motion and Intracochlear Pressure Under Bone Conduction

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Background

Previous research has studied the propagation of sound along the skull's surface and base. Most measurements has been focused on vibration of the promontory or the skull's lateral surface. However, the 3D motion of the temporal bone is not well understood, nor is the relation of promontory motion to intracochlear pressure changes. Recent experimental studies have provided some insight into the relation between temporal bone motion and the intracochlear pressure. This requires further validations, particularly from numerical models that could quantify the complex mechanics of the inner ear under bone conduction excitation.

Aim

The aim of this work is to investigate experimentally and numerically the correlation between the 3D motion of the otic capsule and the intracochlear pressure.

Methods

Experimental data has been collected from six samples from three fresh frozen cadaver heads, including: 3D velocity at 130-200 points across the lateral and medial surfaces of the ipsilateral temporal bone and skull base; 3D motion of a single point at the promontory and stapes; differential intracochlear pressure. Excitation was provided sequentially to the ipsilateral mastoid and classical BAHA location via a percutaneous coupling between 0.1-20 kHz. The experiment was digitally recreated by a custom finite element model (FEM), based on the LiUHead, with the addition of a middle ear and cochlea. The Young modulus of the bone domain within the FEM was varied between 4, 8, and 20 GPa.

Experimental setup and equivalent numerical model

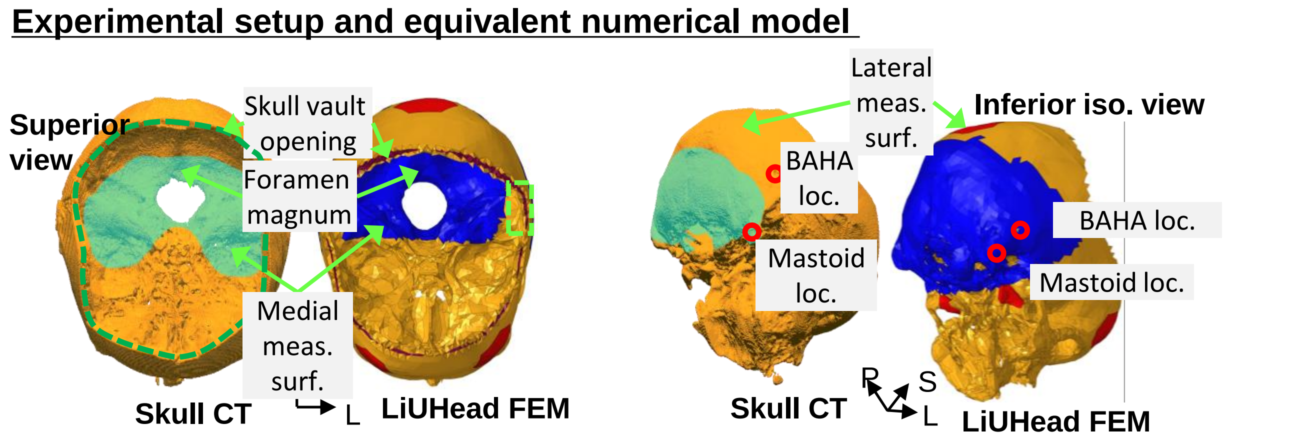

Fig. 1. *Overview of the experimental setup, and its digital "twin" (modified LiUHead FEM), including measurement area at the medial and lateral skull base surface, encompassing the temporal bone and otic capsule.*

Intracochlear pressure and Otic capsule velocity measurements

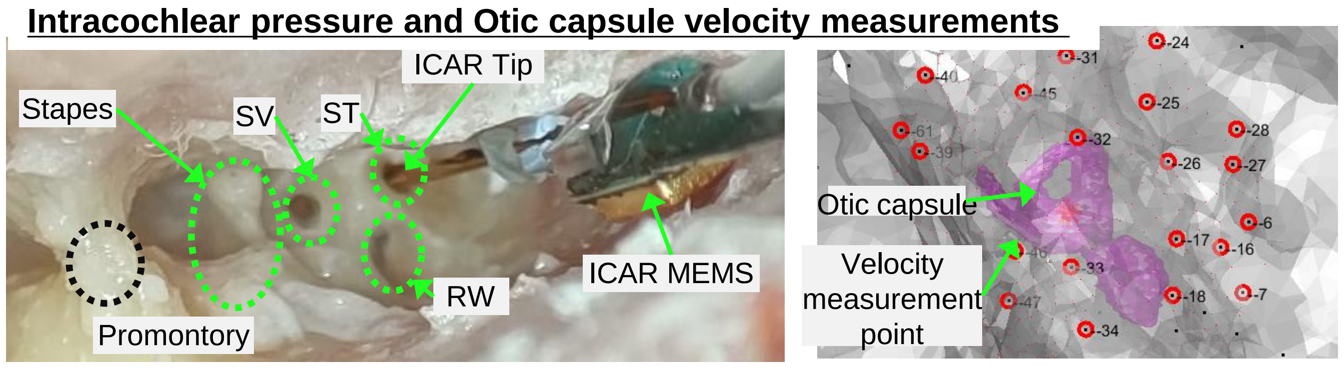

Fig. 2. *Experimental access to intracochlear pressure (left), in scala vestibuli and tympany, and a proxy for the otic capsule motion, based on the 3D velocity of the medial skull surface (right), positioned within less than 2cm of the cochlear center.*

Inner ear model with experimental points of interests

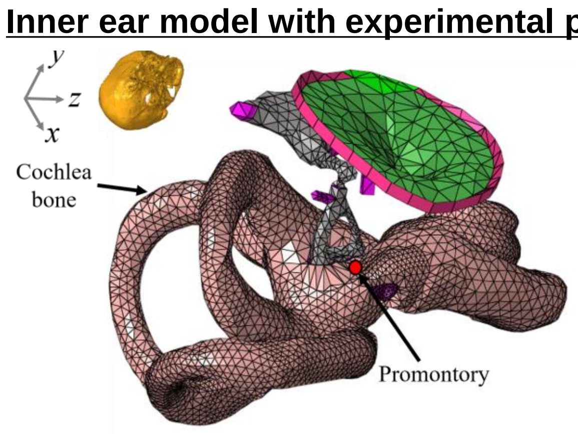

Fig. 3. *Illustration of the ear model within the customized LiUHead FEM. Indicated are the points of: the velocity measurement locations at the promontory and stapes; pressure measurement locations at scala vestibuli and tympany.*

Results

Intracoch. pressure vs. promontory motion correctly predicted by FEM > 1 kHz

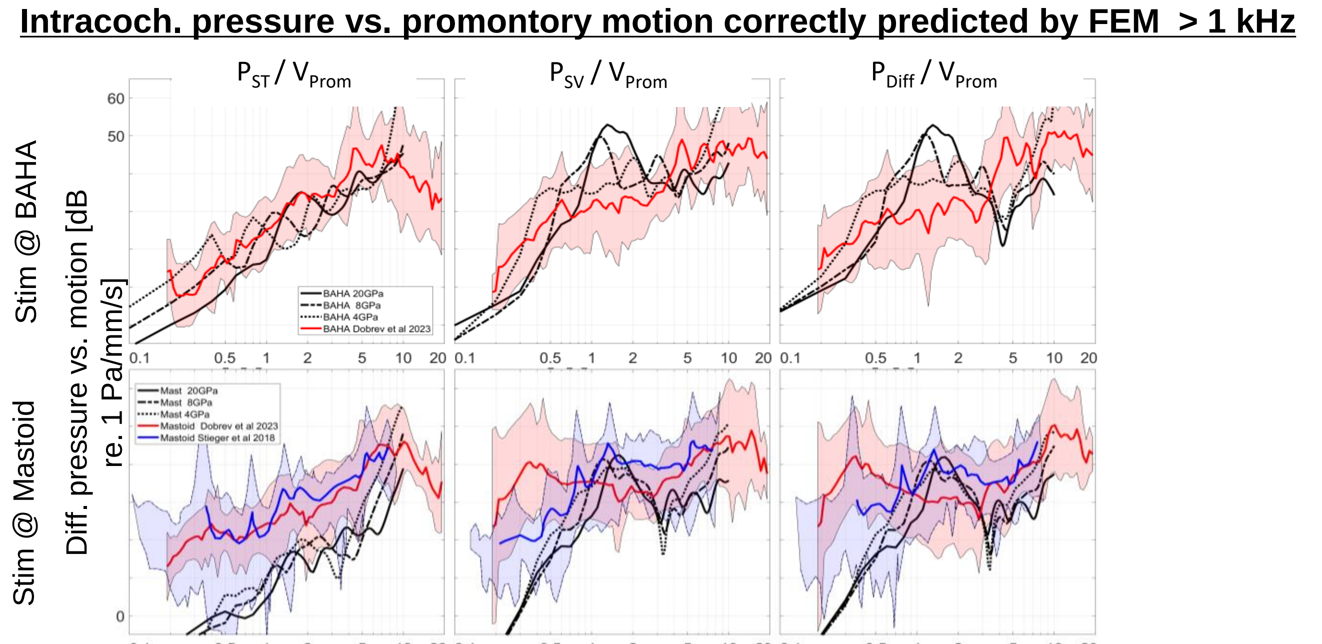

Fig. 4. *Overview of experimental and numerical data of the pressure in scala tympany (left), scala vestibuli (middle) and differential cochlear pressure (right), all normalized by the promontory motion. Numerically predicted data matched experimental measurements above 1kHz, with better fit at lower Young modulus values.*

Results (cont.)

The skull base undergoes a complex 3D deformation

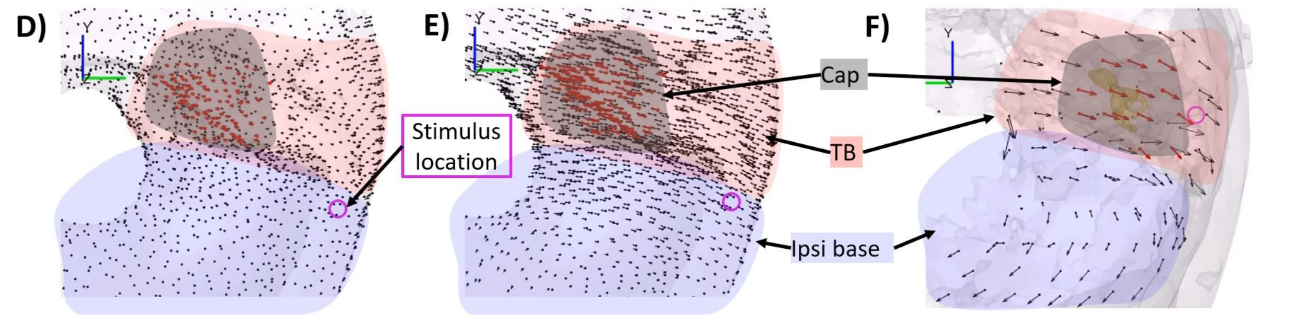

Fig. 5. *Visualization of spatial distribution of the instantaneous amplitude and direction of the 3D velocity vector across the skull base, for 1kHz stimulation at the right mastoid, predicted by the FEM (left and middle column) and a representative cadaver head (right column). Red vectors represent points near the cochleae (yellow surfaces). Highlighted regions indicate the approximate locations of the otic capsule (Cap), temporal bone (TB) and Ipsilateral skull base.*

The otic capsule remains primarily solid across most of the hearing range

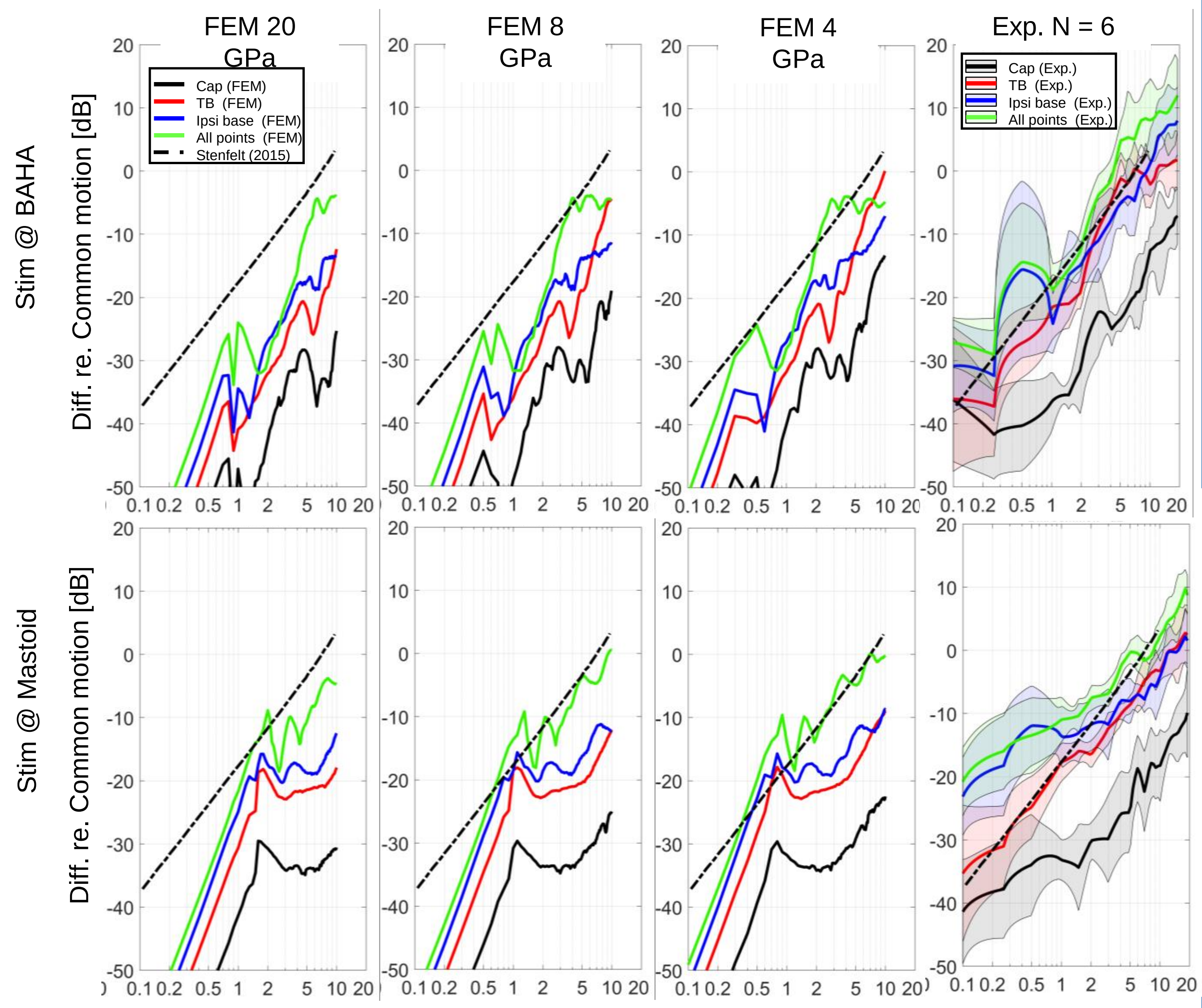

Fig. 6. *Overview of the ratio of differential to common motion at the otic capsule, temporal bone, and ipsilateral skull base, averaged across each ROI. Stimulation was applied at the BAHA (top) and mastoid (bottom) locations, via an implant screw.*

Common and differential motion affect the intracranial pressure differently

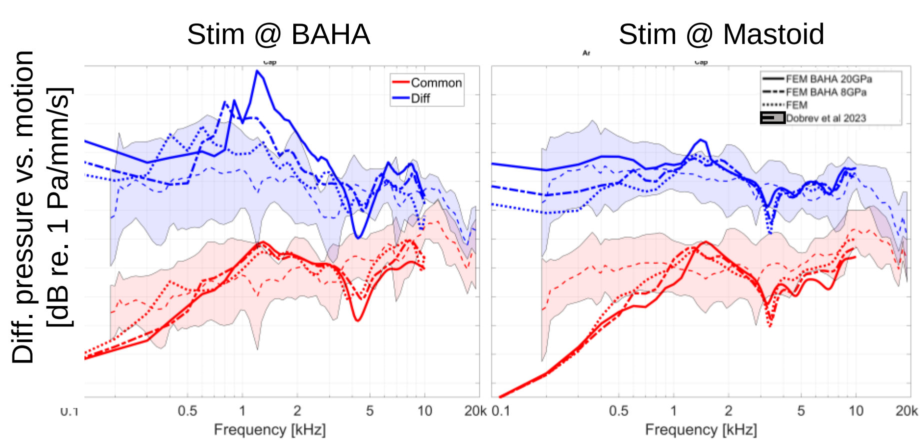

Fig. 7. *Overview of the ratio between P_{DIFF} and the various motion metrics of the otic capsule, based on experimental data and FEM predictions. Young modulus of FEM skull bone was varied between 4, 8 and 20 GPa.*

Conclusions

- Predicted differential intracochlear pressure, normalized by the promontory motion, was within the confidence intervals of the experimental data for most frequencies.
- The spatial variation of the amount of deformation across the skull base, and the otic capsule in particular, was dependent on the material properties of the FEM and closely matched the experimental data.
- The model indicated that the relation between intracochlear pressure and the rigid body motion of the cochlear was affected by the Young modulus of the skull, and it followed the experimentally observed trends.
- Both methods indicated that the otic capsule acted as a rigid accelerometer within the temporal bone, thus exerting primarily inertial load on the cochlear fluid even above 10 kHz.
- Numerical predictions of the resultant otic capsule wall motion indicated predominantly inertial motion, with limited contributions from deformations above 7-10kHz.
- Common motion is the dominant source of volume velocity in the otic capsule.

References

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