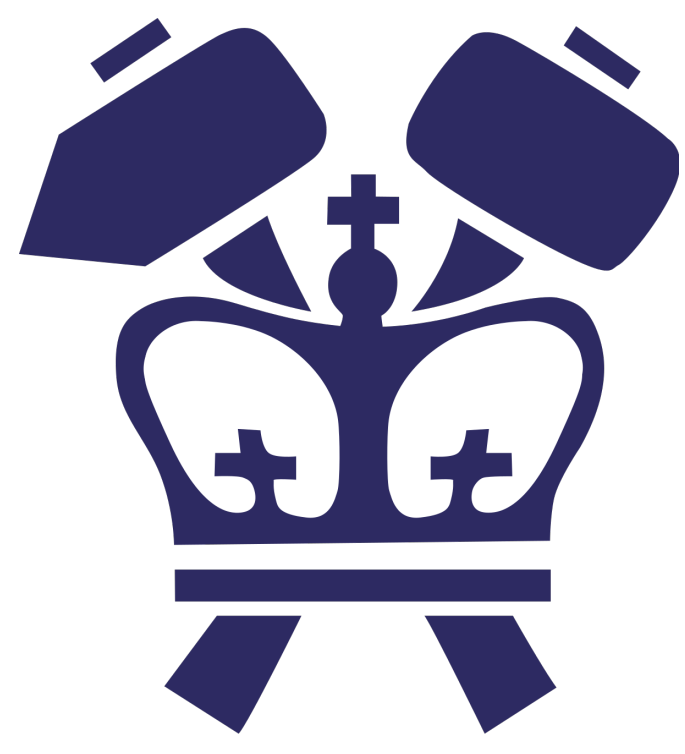




Beyond the Outer Tunnel: Comparisons Across Radial Regions of the Organ of Corti in the Guinea Pig Base

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Introduction

The ‘hotspot’ is where the largest vibrations in the organ of Corti complex (OCC) take place. In gerbil, the hotspot is a large area centered around the outer hair cell (OHC)/Deiters’ cell (DC) junction. Unlike the basilar membrane (BM), the hotspot’s motion is compressively nonlinear across frequencies (Cooper *et al.* 2018). In guinea pig, the hotspot has a more restricted area centered closer to the OHC apices and reticular lamina (RL) region. However, the hotspot does not extend beyond the outer tunnel in either animal model.

The area lateral of the outer tunnel, the lateral region, is home to supporting cells, including Hensen’s cells and Claudius’ cells. In the base, there are also densely packed Boettcher’s cells that sit on the BM. These cells bridge the OCC to the spiral ligament and are part of the overall OCC motion. Therefore, characterizing their motion is vital to understanding the OCC as a whole.

Methods

- Animal model: Juvenile guinea pigs between 200-350 g.
- A small opening in the bulla was made caudally to the external ear canal to expose the round window (RW).
- Cochlear condition was monitored with $2f_1 - f_2$ distortion product otoacoustic emissions (DPOAEs).
- One second, multi-tone (zweis) stimuli were presented at 50, 60, 70, and 80 dB sound pressure level (SPL).
- Motion measurements were made through the RW with the Telesto III optical coherence tomography (OCT) system.
- Longitudinal, radial, and transverse projections onto optical axis were found using the program outlined in Frost *et al.* 2022.
- Data presented are a representative dataset from GP86 runs 52-54. Results are consistent across experiments.

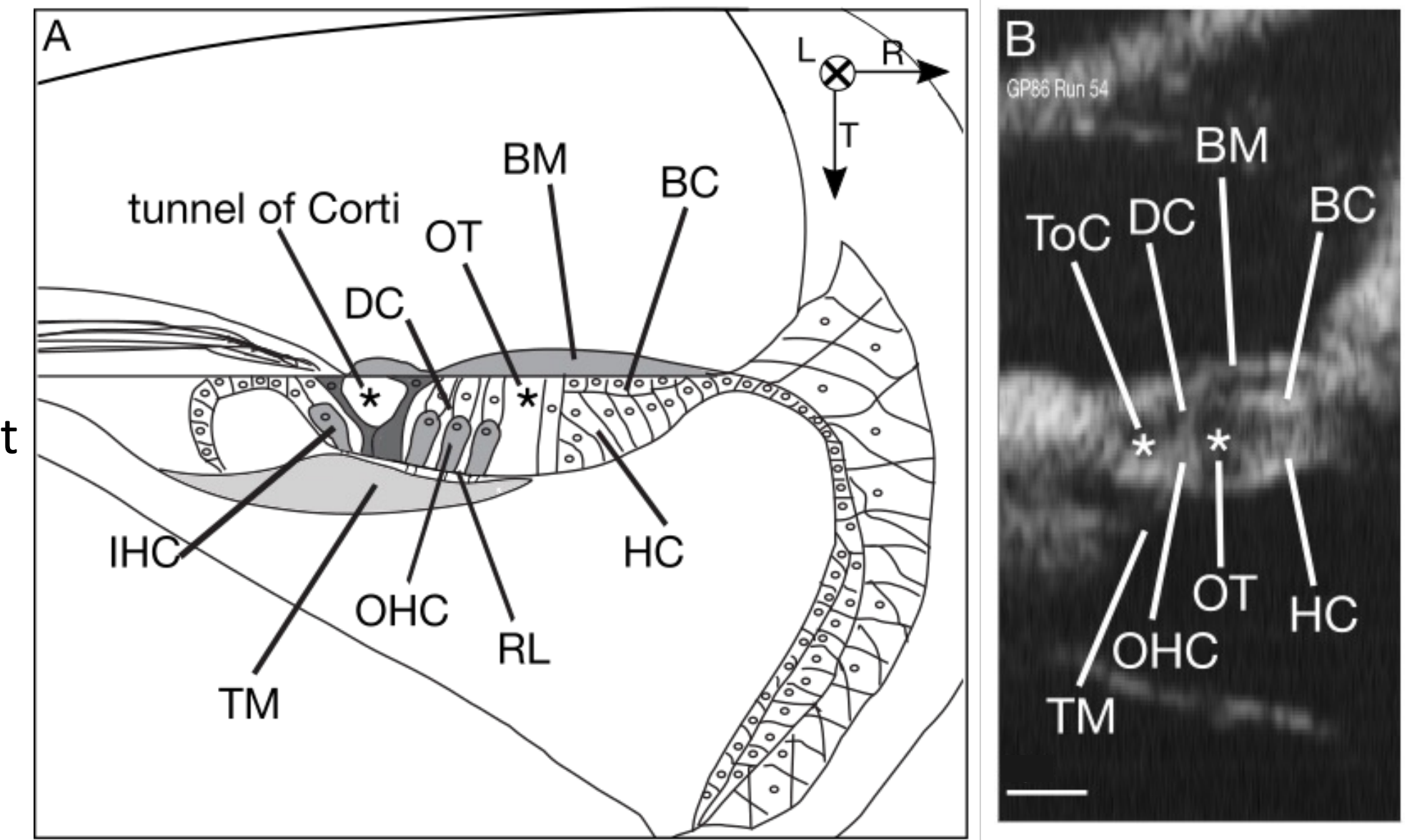


Figure 1: (A) Simplified rendering of a radial-transverse cross-section of the organ of Corti in the base. Structures of interest are the basilar membrane (BM), tectorial membrane (TM), outer hair cells (OHCs), Deiters’ cells (DC), reticular lamina (RL), Boettcher’s cells (BC), and Hensen’s cells (HC). (B) OCT Bscan of an approximately radial-transverse cross-section identifying the anatomy. Stars indicate fluid tunnel locations. Scale bar = 50 μm .

Results

- Best frequency is approximately 34 kHz
- Longitudinal, radial, and transverse components of the optical axis are (0.2, -0.4, 0.9)
- Medial and lateral regions separated by approximately 100 μm
- Medial region: medial BM and OHC apices/RL region
- Lateral region: lateral BM, Boettcher’s cells, and Hensen’s cells
- Guinea pig hotspot activity was restricted to a small area close to the OHC apices/RL region
- Hensen’s cells apices and Boettcher’s cells were approximately in phase with lateral BM
- Medial OHC apices/RL region phases were in phase with BM near BF, but increased in phase difference at low frequencies
- Boettcher’s cells in lateral region move like BM
- Hensen’s cell apices move less than lateral BM and Boettcher’s cells
- Medial BM and RL region pixels separated by 67.5 μm
- Lateral BM and Boettcher’s pixels separated by 40.5 μm and lateral Boettcher’s and Hensen’s apices separated by 48.6 μm

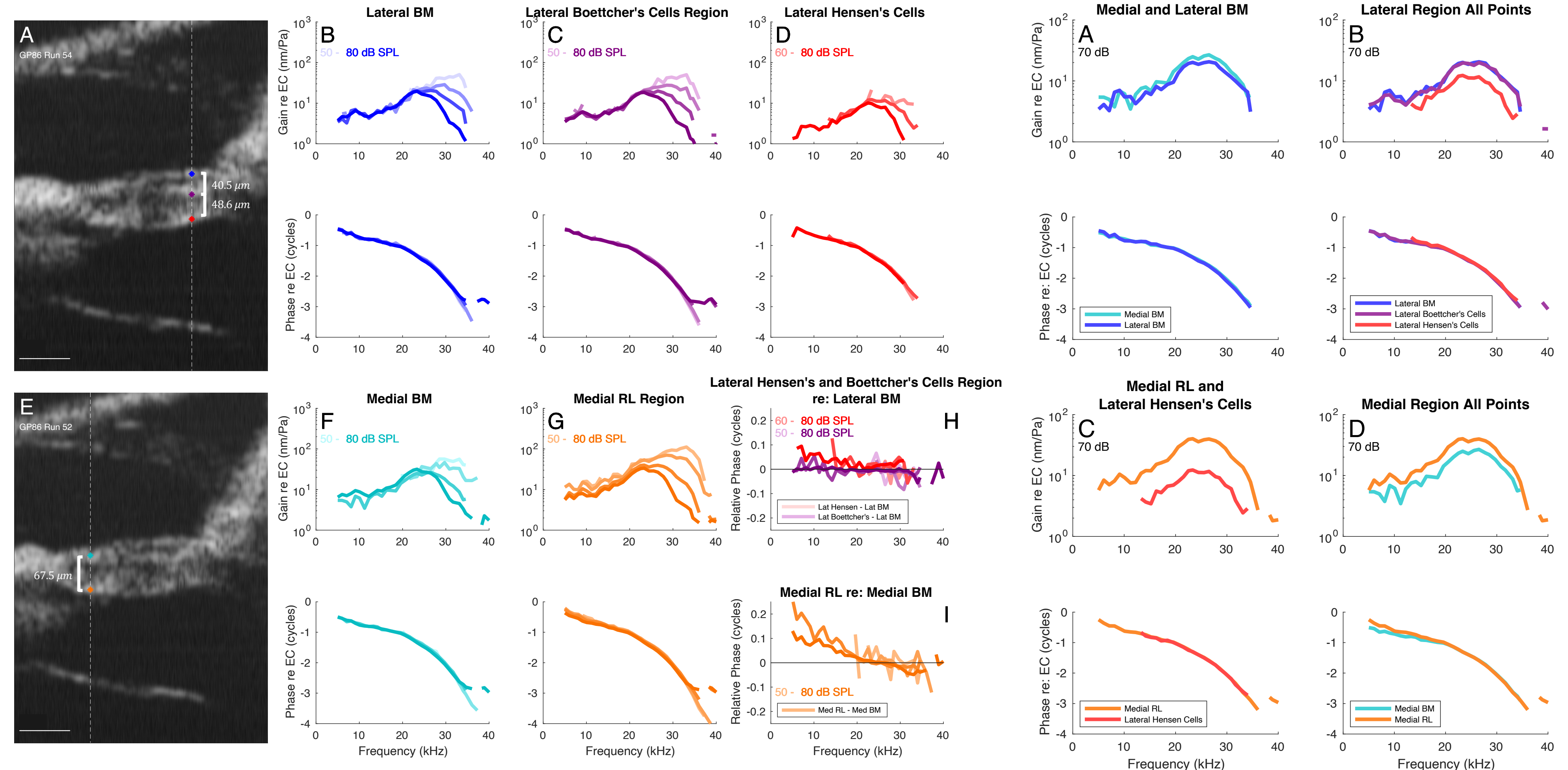


Figure 2: GP86 run 52 and 54 Bscans, gain, and phase. (A) Bscan for GP86 run 54, the lateral region. White dashed line indicates the axis of the Bscan along which vibrometry data were taken. Colored stars indicate locations in depth from which featured vibrometry data were taken (BM - blue, Boettcher’s cells - purple, Hensen’s cells - red). Scale bar = 50 μm . (B-D) Gain in nm/Pa (top) and phase re: ear canal pressure in cycles (bottom) from the BM (BM), Boettcher’s cells (C), and Hensen’s cells (D). (E) Bscan for GP86 run 52, the medial region. Colored stars indicate locations in depth from which featured vibrometry data were taken (cyan - BM, orange - RL). Scale bar = 50 μm . (F-G) Gain in nm/Pa (top) and phase re: ear canal pressure in cycles (bottom) from the BM (F), and RL region (G). (H) Lateral Hensen’s cells and Boettcher’s cells phase re: lateral BM. (I) Medial RL region phase re: medial BM.

Figure 3: GP86 run 52 and 54 Bscans, gain, and phases replotted to compare motion of different locations. Selected 70 dB SPL results from Figure 2. (A) Medial and lateral BM gain (top) and phase (bottom) at 70 dB SPL. (B) Lateral BM, Boettcher’s cells, and Hensen’s cells region gain (top) and phase (bottom) at 70 dB SPL. (C) Medial RL region and lateral Hensen’s cells gain (top) and phase (bottom) at 70 dB SPL. (D) Medial BM and RL region gain (top) and phase (bottom) at 70 dB.

Discussion

- The difference between a fluid-like vs. a solid body-like lateral region is the amount of OCC mass.
- From classical 2D cochlear model: Effective fluid mass = $m_{fl\text{eff}}$
- Define effective OCC mass = $m_{OC\text{eff}}$

$$\text{Fluid} \quad m_{fl\text{eff}} = \rho h_{fl\text{eff}} = \frac{\rho}{k} \quad \text{Solid body} \quad m_{OC\text{eff}} = \rho h_{OC\text{eff}}$$

$$m_T = m_{fl\text{eff}} + m_{OC\text{eff}}$$

$$\frac{1}{2} m_T (\omega x)^2 = \frac{1}{2} S x^2$$

$$S = m_T \omega^2$$

$$S = \omega^2 \left(\rho h_{OC\text{eff}} + \frac{\rho}{k} \right)$$

$$\text{OCC Fluid-like: } \rho h_{OC\text{eff}} \ll \frac{\rho}{k}$$

$$\text{Wave speed: } \frac{\omega}{k} = \frac{S}{\omega \rho}$$

OCC Solid body-like:
large $h_{OC\text{eff}} \rightarrow$ large $m_{OC\text{eff}}$
Slows down traveling wave – shifts peak closer to the base

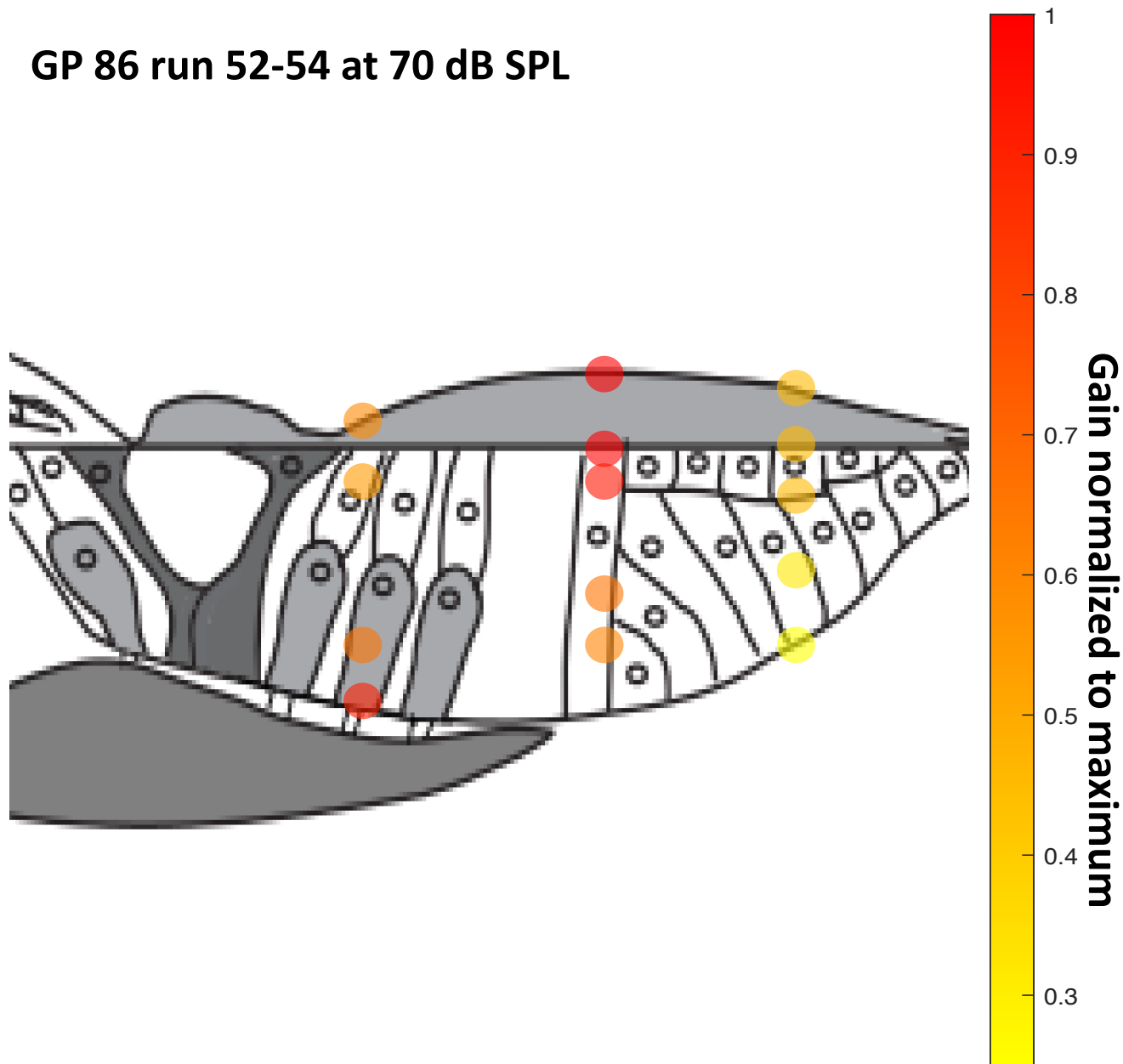


Figure 4: Simulated heat map of gain at three radial locations normalized to the largest gain. Data are overlaid on the simplified rendering from Figure 1A in their approximate positions. Data are from the gain at 70 dB SPL from GP86 run 52 (medial), 53, (central), and 54 (lateral). Gain is largest in the center of BM and at the RL region. Gain is smallest at the Hensen’s cells apices.

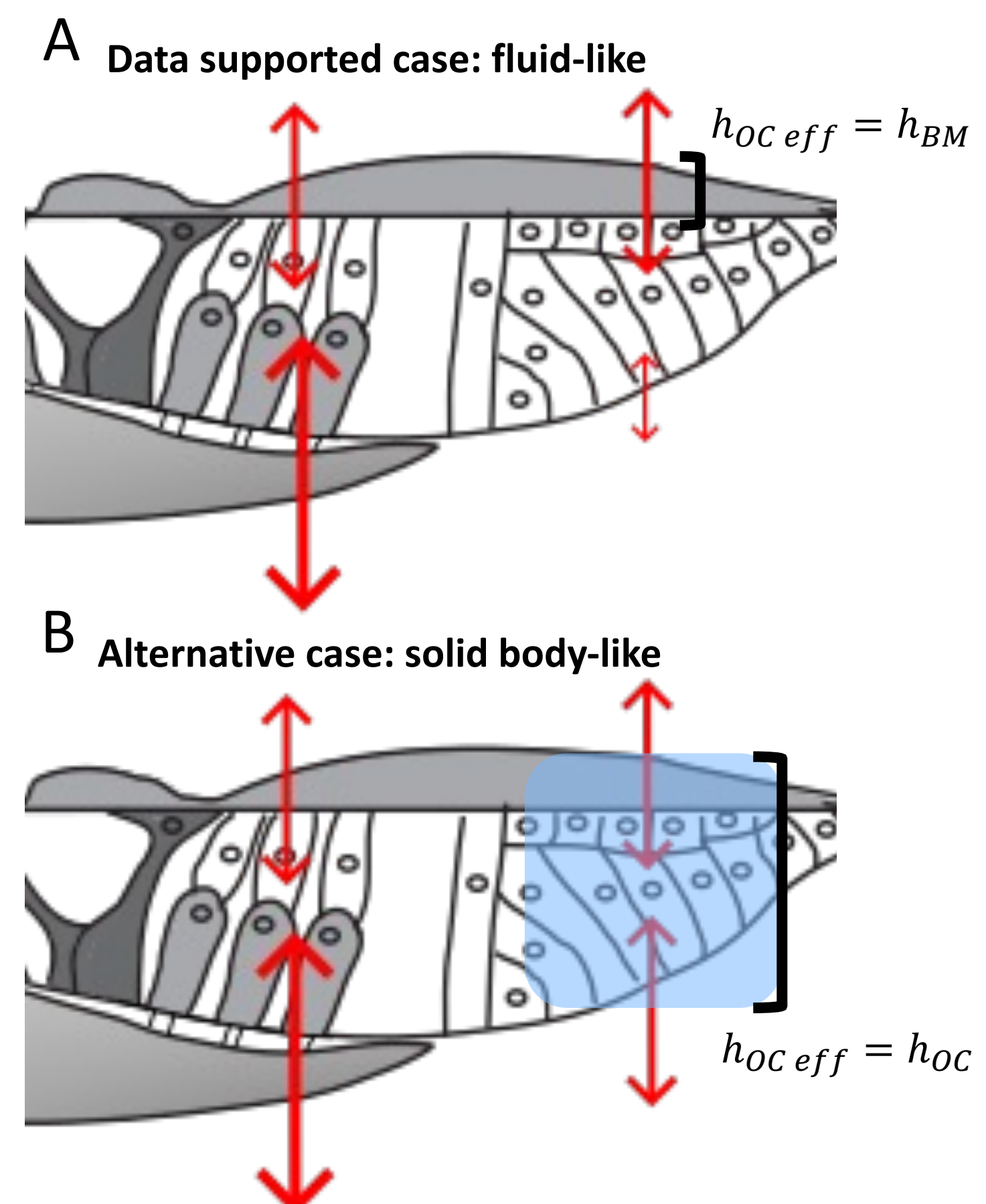


Figure 5: (A) Simplified rendering from Figure 1A overlaid with arrows. The arrows’ length and thickness correspond to the relative amount of motion in the medial BM, medial RL region, lateral BM, and lateral Hensen’s cells apices. These relative motions are supported by the data presented in Figures 2-4. The RL region moves most, and the medial and lateral BM move less than the RL region but approximately the same as each other. The Hensen’s cells apices move substantially less than lateral BM, indicating they are fluid-like. The effective OCC height for the fluid-like case is the height of the BM (B) The same simplified rendering as Figure 5A, but in solid body-like case where the Hensen’s cells apices move like BM. Therefore, the entire OCC height is included in the effective OCC height.

References

- Cooper, N. P., Vavakou, A., & van der Heijden, M. (2018). Vibration hotspots reveal longitudinal funneling of sound-evoked motion in the mammalian cochlea. *Nature Communications*, 9, 3054. <https://doi.org/10.1038/s41467-018-05483-z>
- Frost, B. L., Strimbu, C. E., & Olson, E. S. (2022). Using volumetric optical coherence tomography to achieve spatially resolved organ of Corti vibration measurements. *The Journal of the Acoustical Society of America*, 151(2), 1115–1124. <https://doi.org/10.1121/10.0009576>
- Lighthill, J. (1981). Energy flow in the cochlea. *Journal of Fluid Mechanics*, 106(1), 149. <https://doi.org/10.1017/S0022112081001560>
- Strimbu, C. E., Chiriboga, L. A., Frost, B. L., & Olson, E. S. (2024). Regional differences in cochlear nonlinearity across the basal organ of Corti of gerbil. *Hearing Research*, 108951. <https://doi.org/10.1016/j.heares.2024.108951>

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