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A Biological Gear in the Human Middle Ear

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Frequency Range of Hearing

- Most amphibians, fish, reptiles: < 5 kHz
- Birds: < 8-12 kHz
- Non-mammalian vertebrates: < 10 kHz
- Vertebrate Mammals: < 200 kHz

What special in mammals?

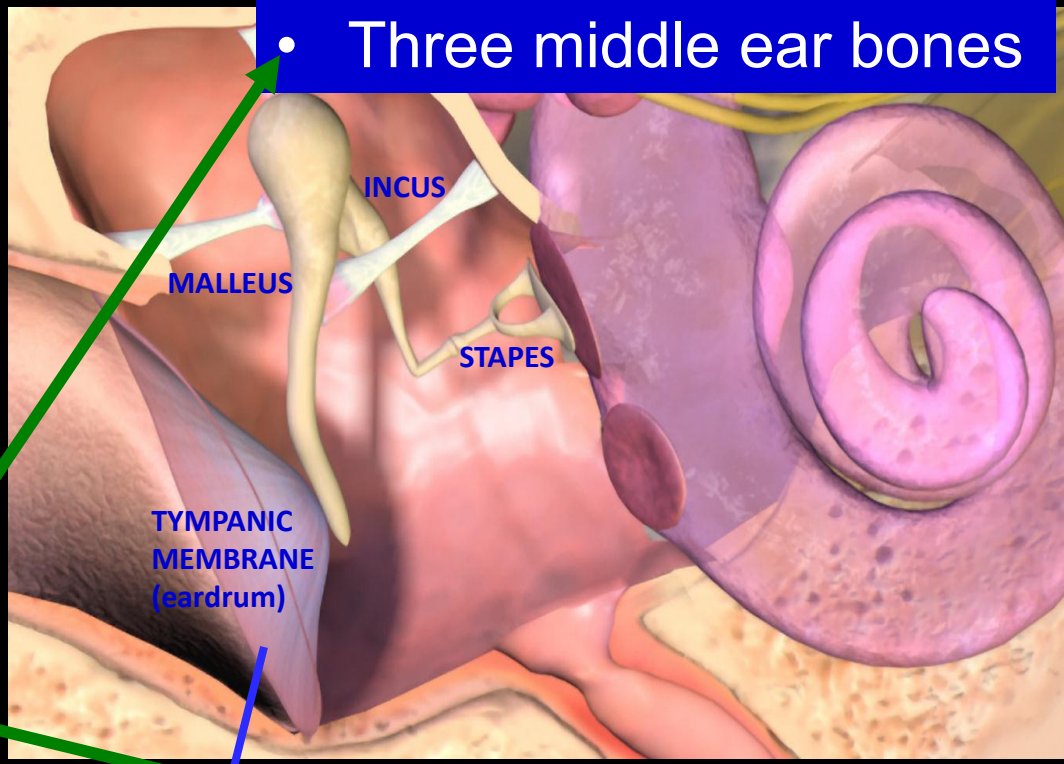
Google define:mammals Search

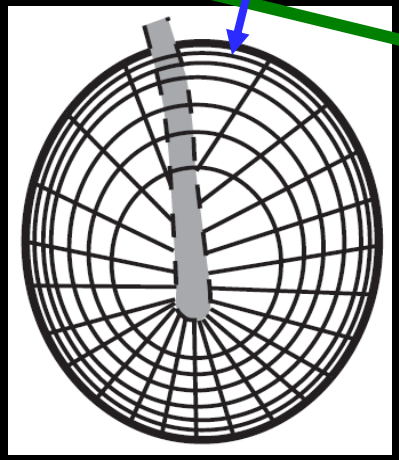
- ✖ Mammal were an Australian band that formed in March 2006. …
- ☺ Mammals (formally Mammalia) are a class of vertebrate, characterized by being warm-blooded, having hair, feeding milk to their young, …, having **three middle ear bones** used in hearing, …

Mechanics Unique to Mammals

Mammals' ability to hear high frequency sounds is due to the unique structures in their hearing organ including

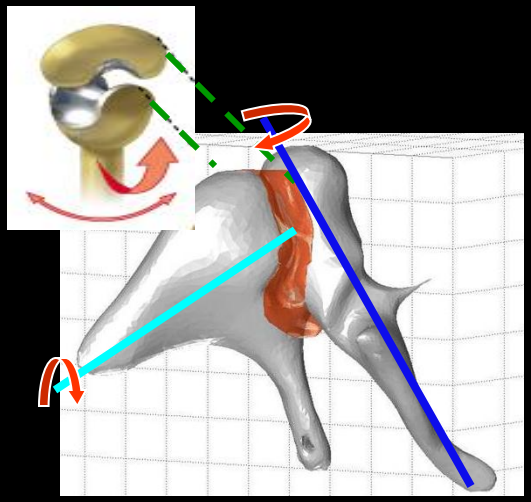
- Three middle ear bones



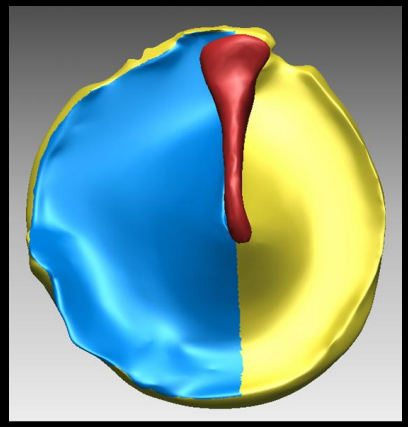


- Distinct radial and circumferential collagen fiber layers in the eardrum

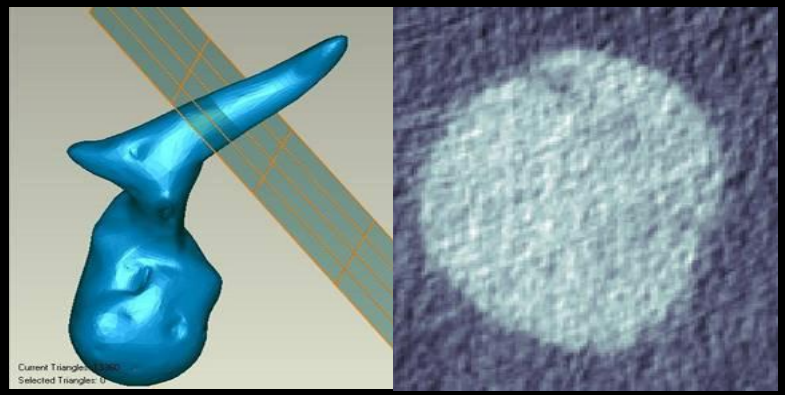
The Shape and connecting mechanism of the ME bones are further distinctive in larger mammals like human !



Mobile saddle-shaped joint



Asymmetric eardrum



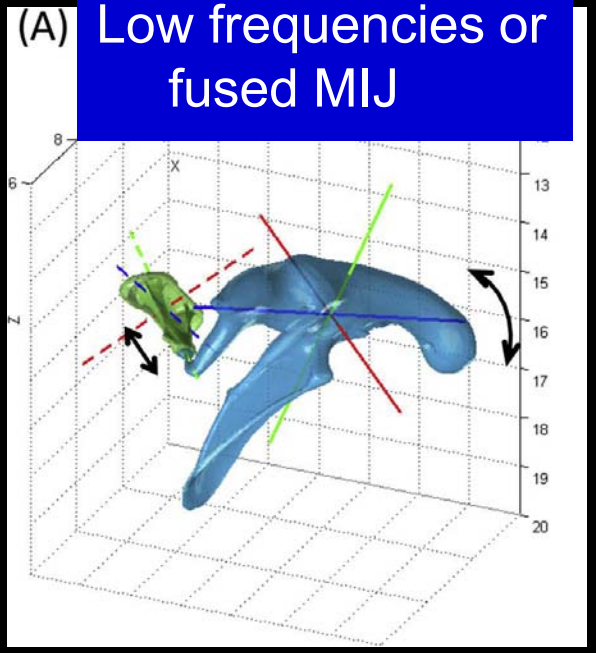
Cylindrical malleus shape

Favorable to the existence of complex twisting motion at the MIJ !!

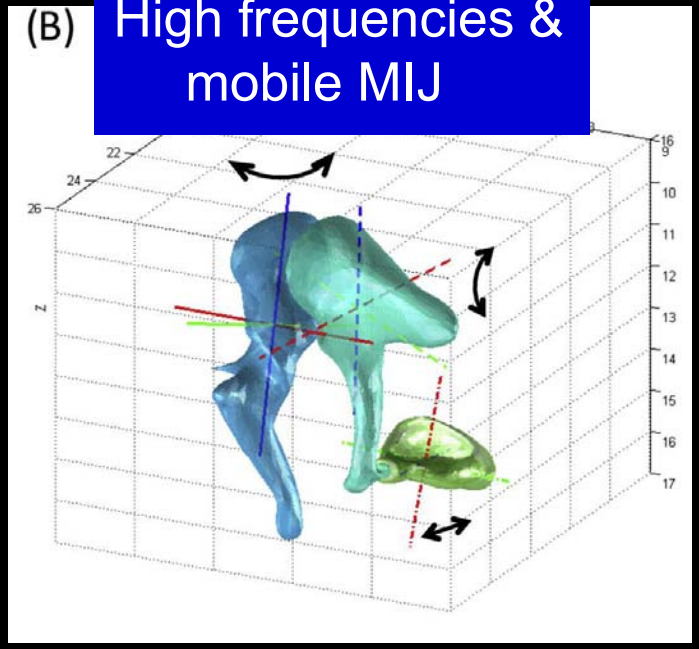
Hypothesis

- **The mobile saddle-shaped malleus-incus joint forms a “gear mechanism” at high frequencies.**

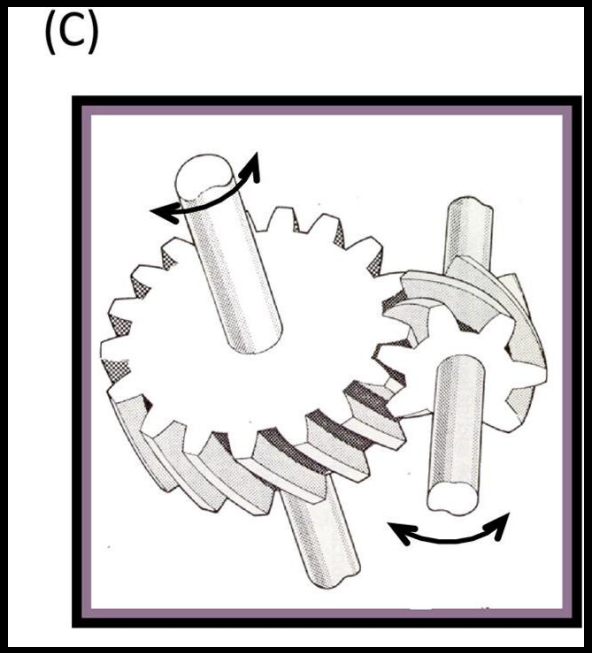
(A) Low frequencies or fused MIJ



(B) High frequencies & mobile MIJ



(C)

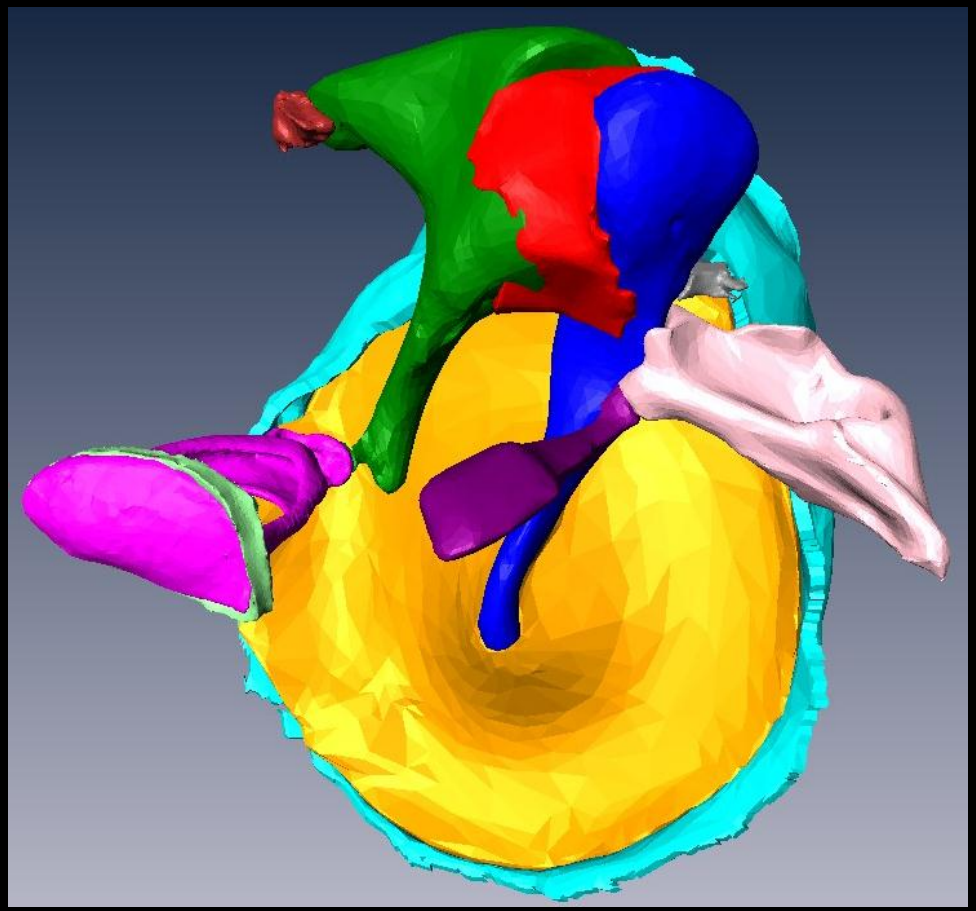


Classical hinging motion

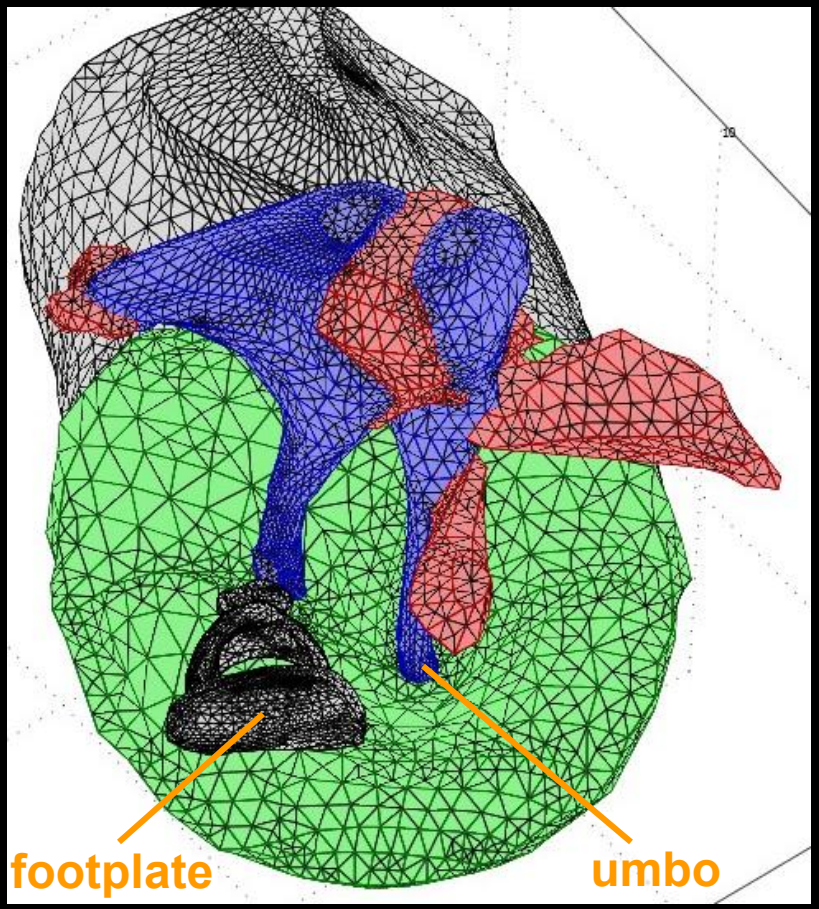
Gear mechanism

Method

FE simulation of acoustics-structure interaction

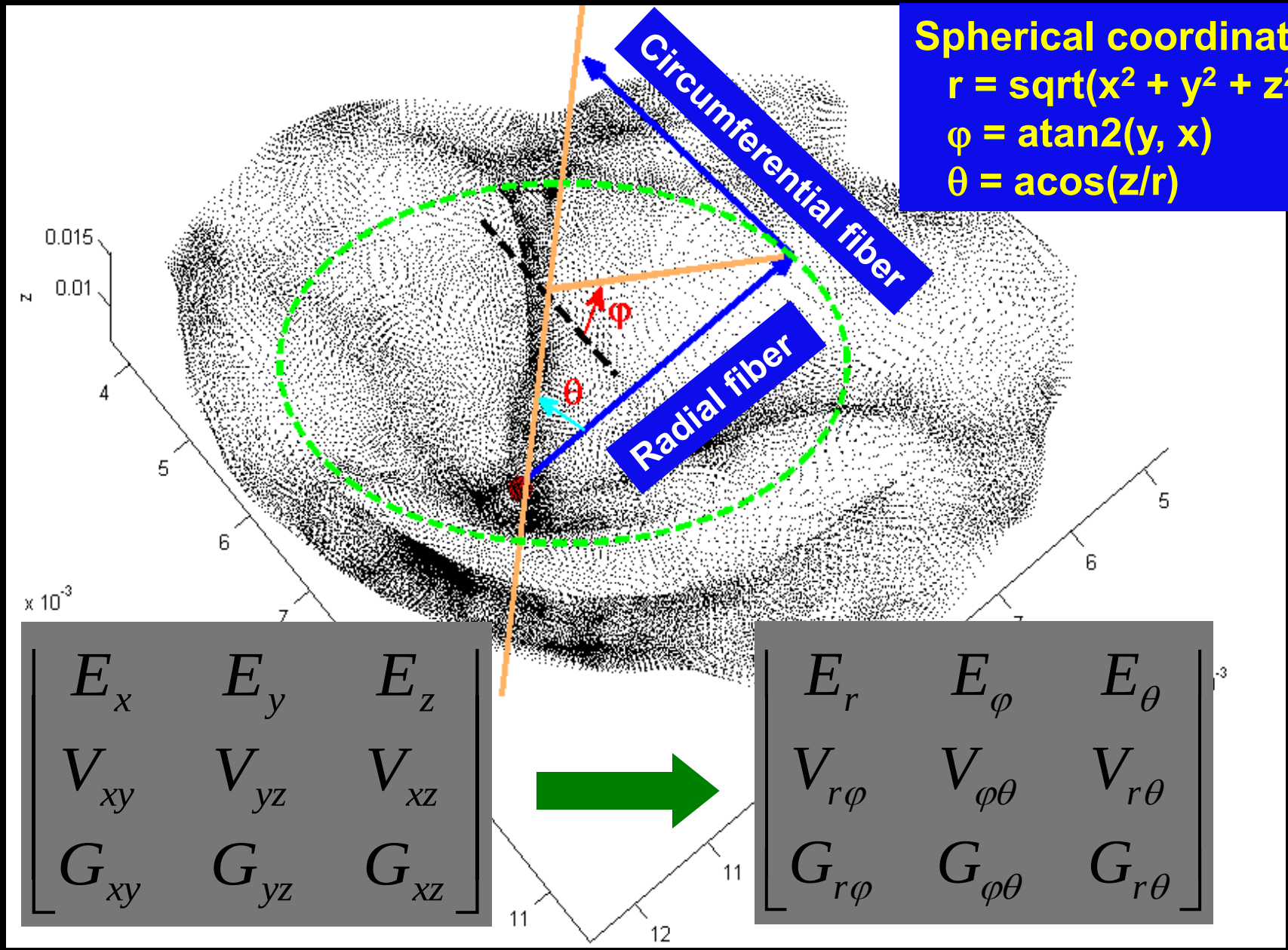


3D reconstruction from μCT images



FE mesh

Effects of eardrum orthotropy on ME mechanics

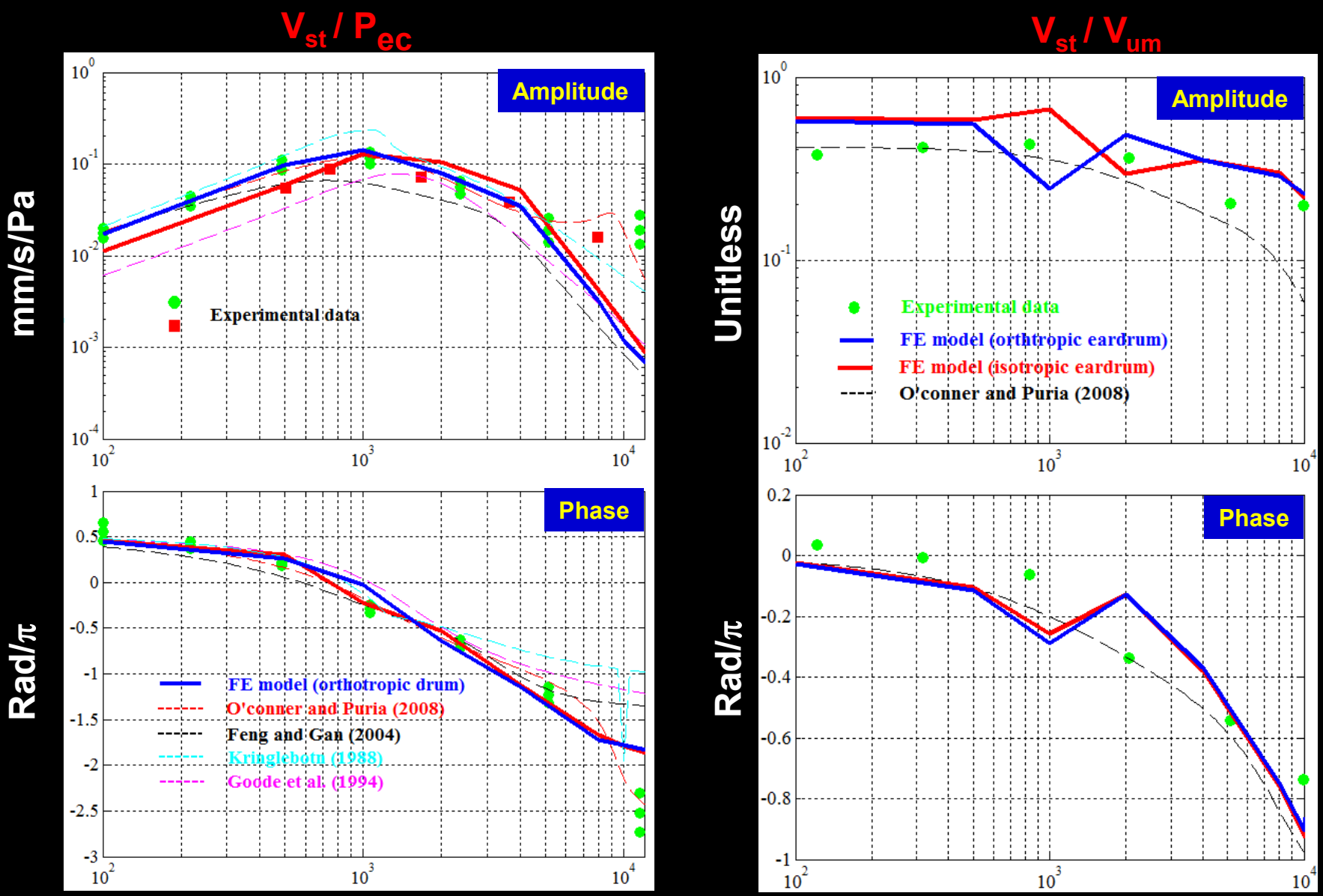


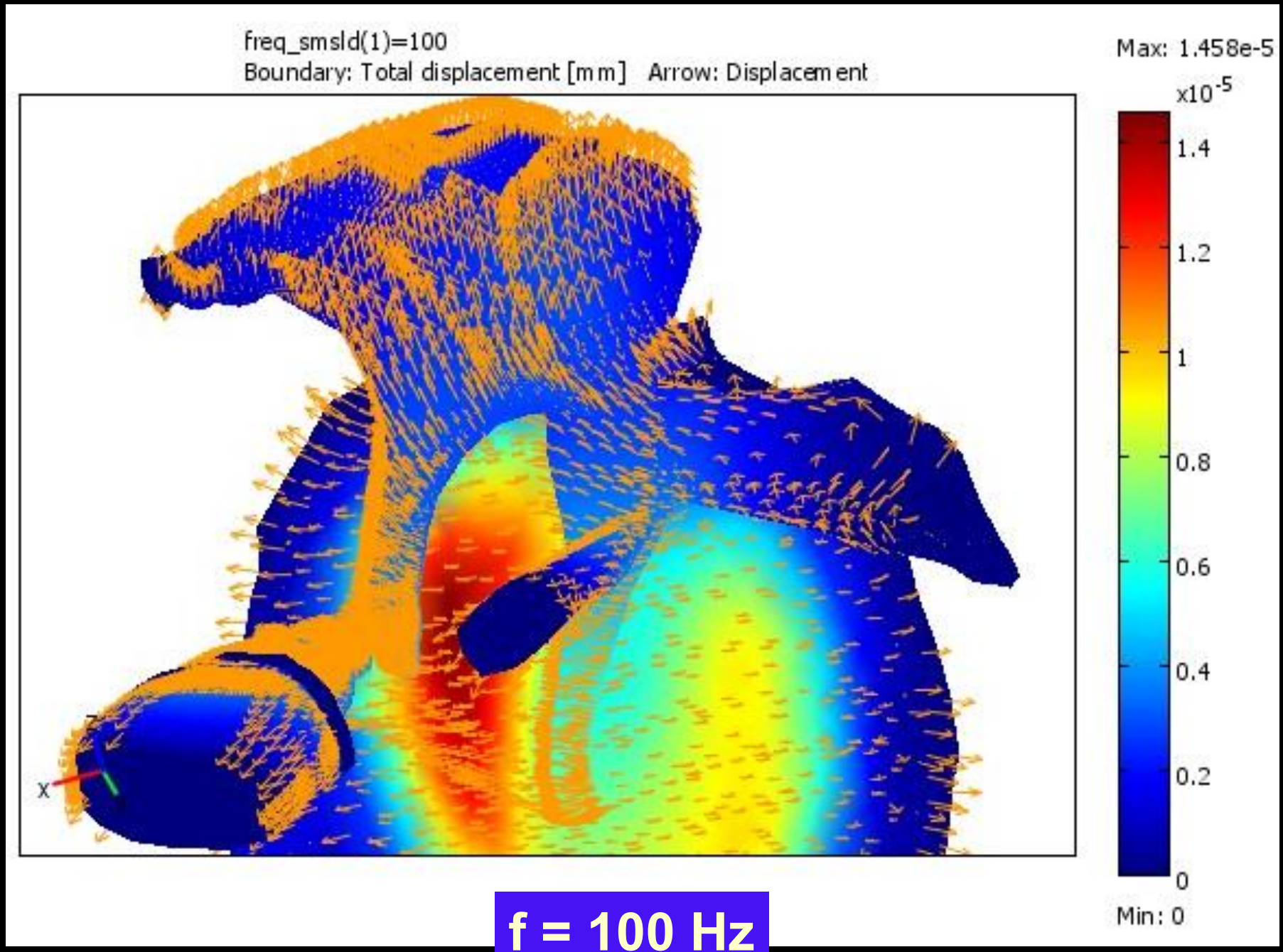
$$\begin{bmatrix} E_x & E_y & E_z \\ V_{xy} & V_{yz} & V_{xz} \\ G_{xy} & G_{yz} & G_{xz} \end{bmatrix}$$

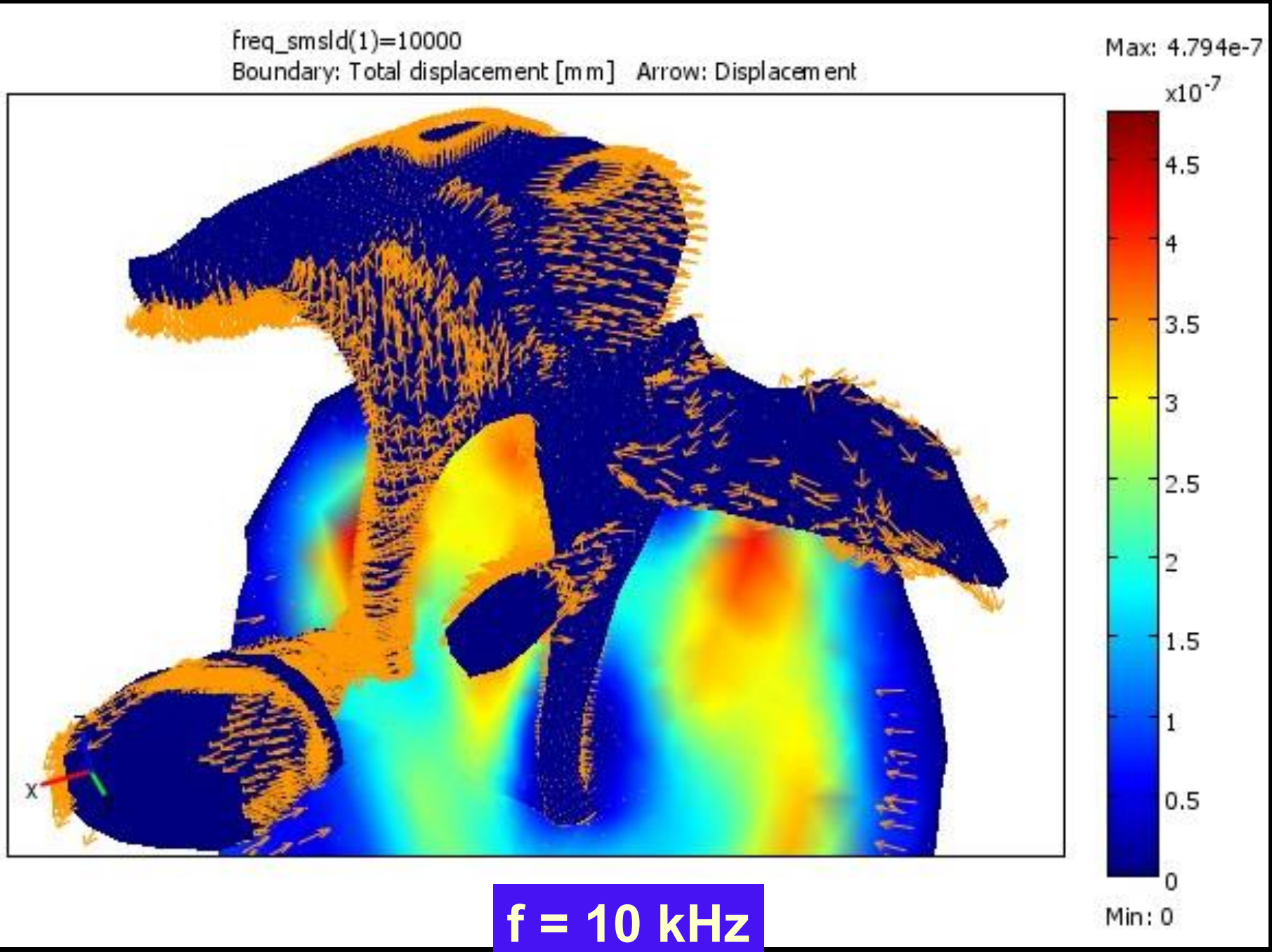
$$\begin{bmatrix} E_r & E_\varphi & E_\theta \\ V_{r\varphi} & V_{\varphi\theta} & V_{r\theta} \\ G_{r\varphi} & G_{\varphi\theta} & G_{r\theta} \end{bmatrix}$$

Validation

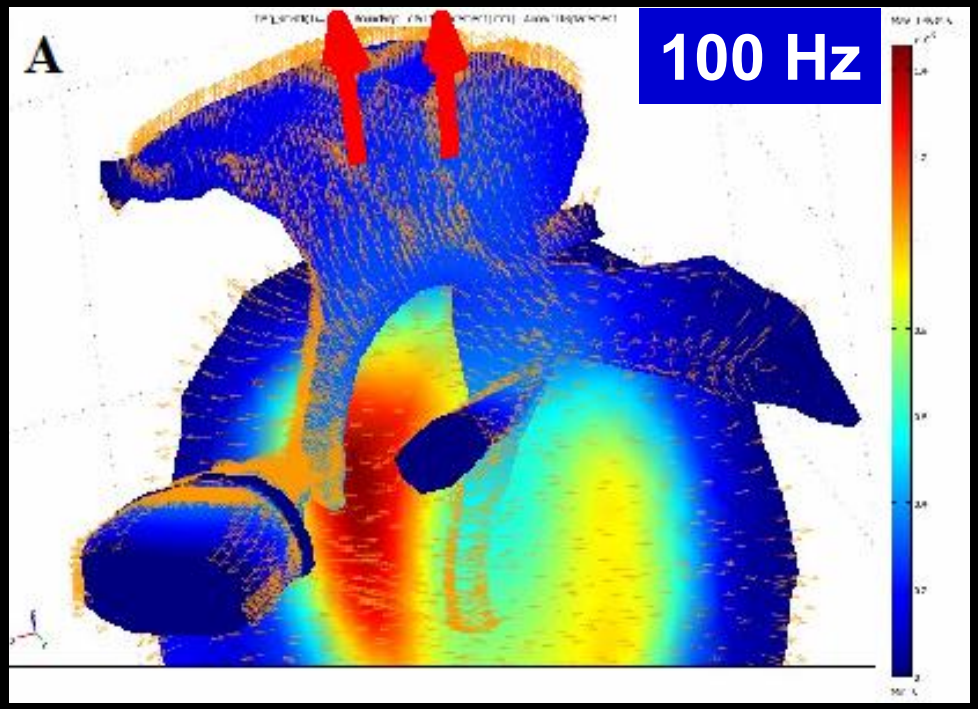
Comparison with experimental data

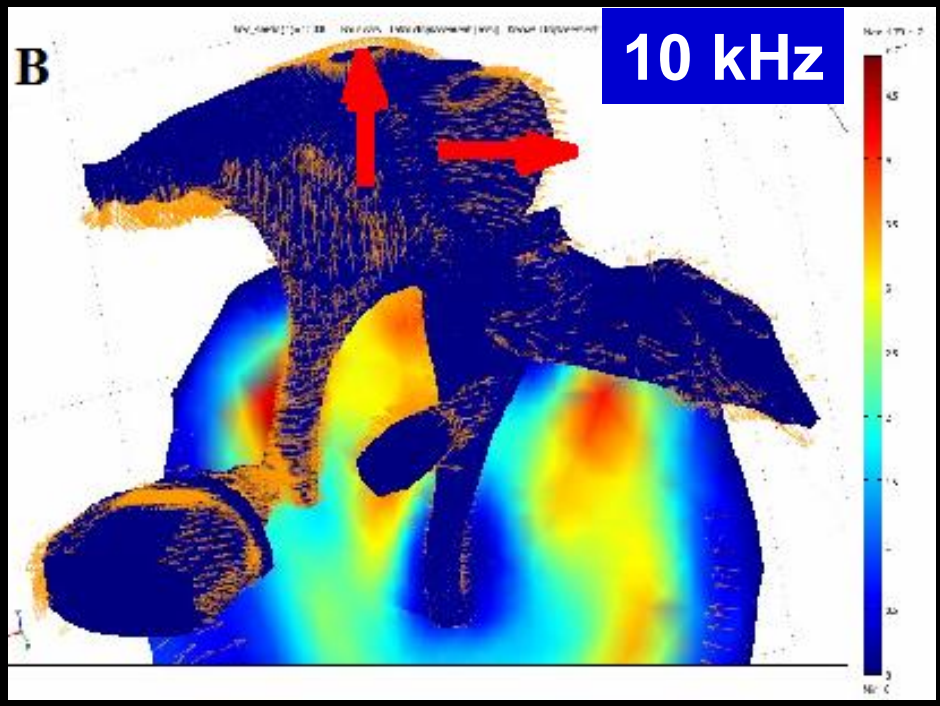



freq_smsld(1)=100
Boundary: Total displacement [mm] Arrow: Displacement
Max: 1.458e-5
x10-5
1.4
1.2
1
0.8
0.6
0.4
0.2
0
Min: 0
x
f = 100 Hz


freq_smsld(1)=10000
Boundary: Total displacement [mm] Arrow: Displacement
Max: 4.794e-7
x10-7
4.5
4
3.5
3
2.5
2
1.5
1
0.5
0
Min: 0
X
f = 10 kHz

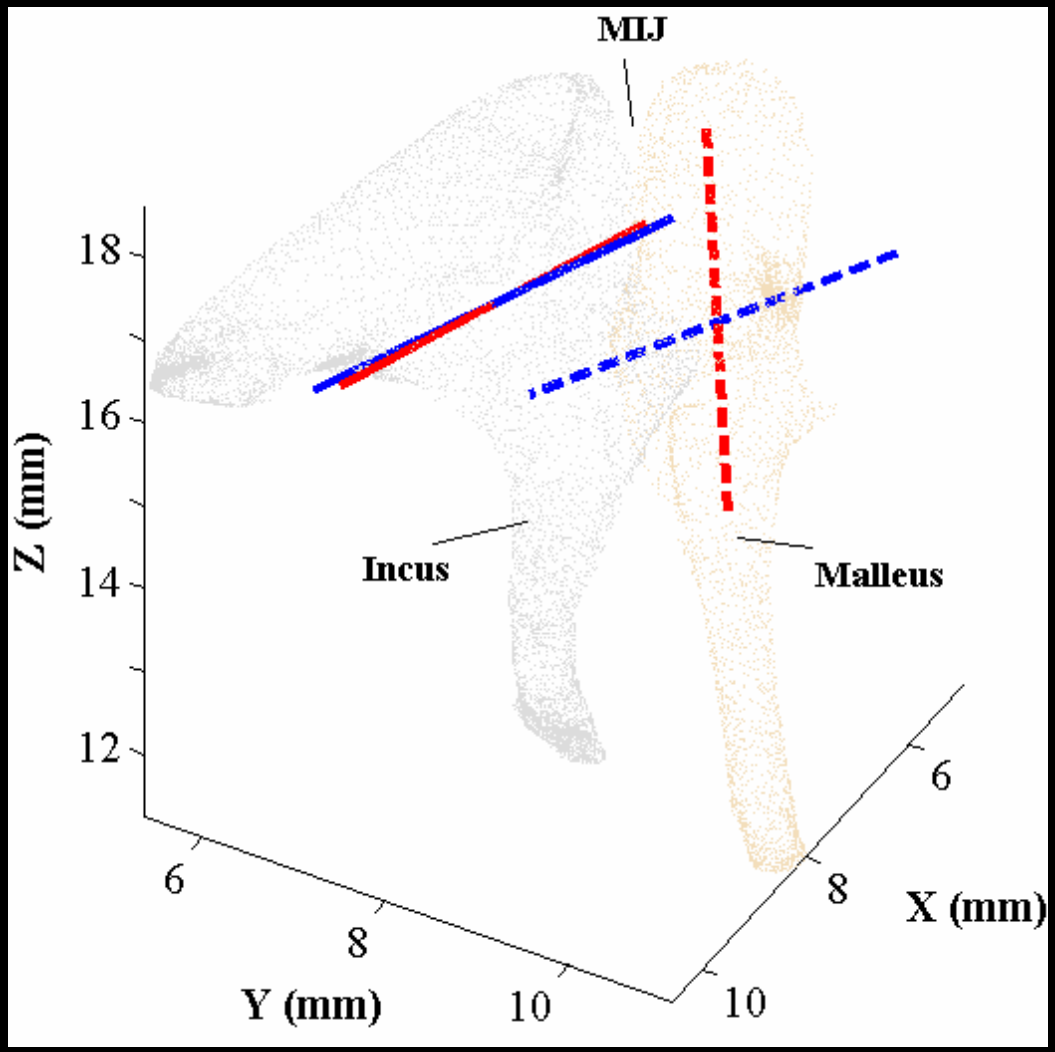
Displacement fields of ME structures





- Different motion modes of ME structures at low and high frequencies at the MIJ.
- Multi-resonance vibration modes at the eardrum were observed at 10 kHz.

Rotation axes of malleus and incus



- The average rotation axes of malleus (dash lines) and incus (solid lines) are parallel (blue lines) at 100 Hz (*hinging motion*), while those at 10 kHz (red lines) are perpendicular to each other (*indicative of a bevel-gear like mechanism*).

Conclusion

- At low frequencies, hinge-like motion is dominant, as expected, and that the orthotropy of the eardrum boosts the ME gain due to increased peak displacement.
- At high frequencies, we observe multi-resonance vibration modes at the eardrum and a bevel-gear-like motion at the MIJ, and the orthotropy of the eardrum makes the rotation axis of the malleus more coincident with its long axis.

Conclusion

- Human middle ear motion modes and dynamics are determined by its special anatomical features. The twisting mode of the malleus and incus is required for efficient high-frequency sound transmission in larger mammals whose large ossicular mass would otherwise produce significant moment of inertia.

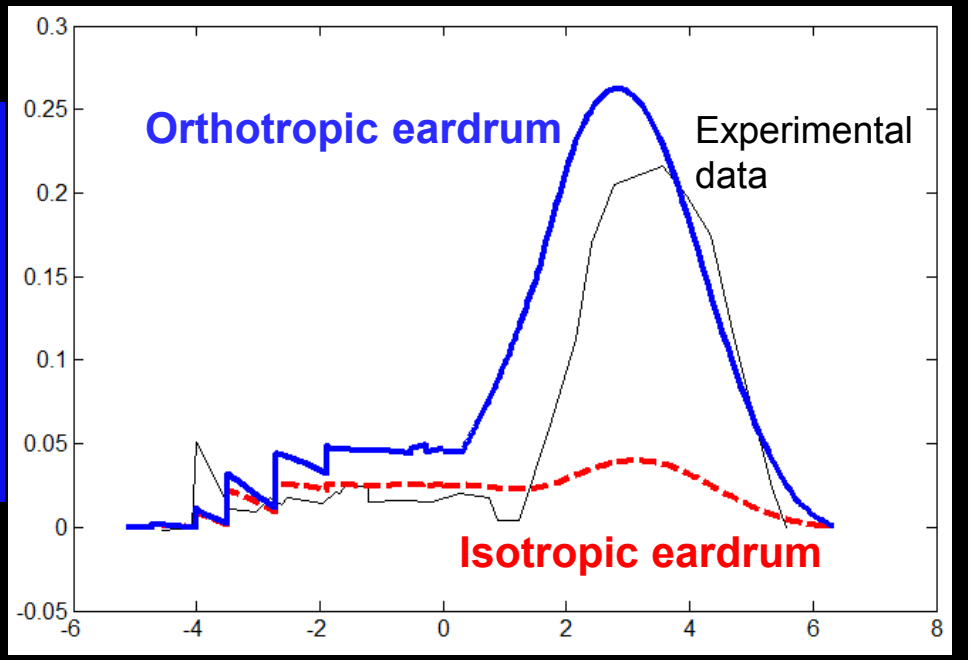
Acknowledgements

This work was supported by Grant No. R01 DC 005969 and ARRA supplements from the NIDCD of the NIH.

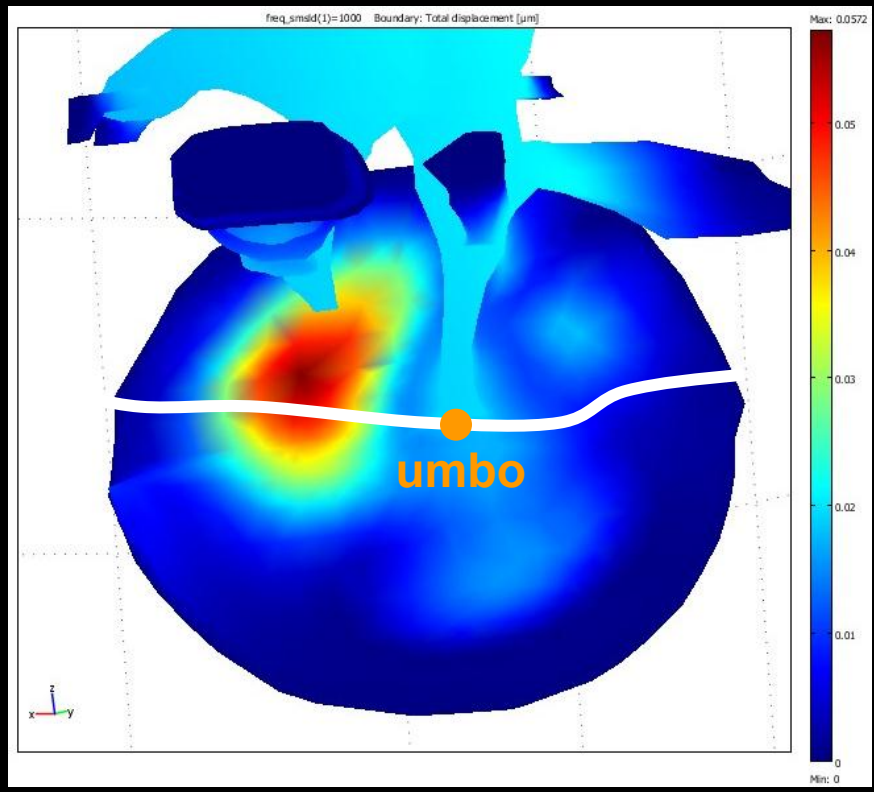
Thank you !

Effects of eardrum orthotropy on ME mechanics

Eardrum displacement

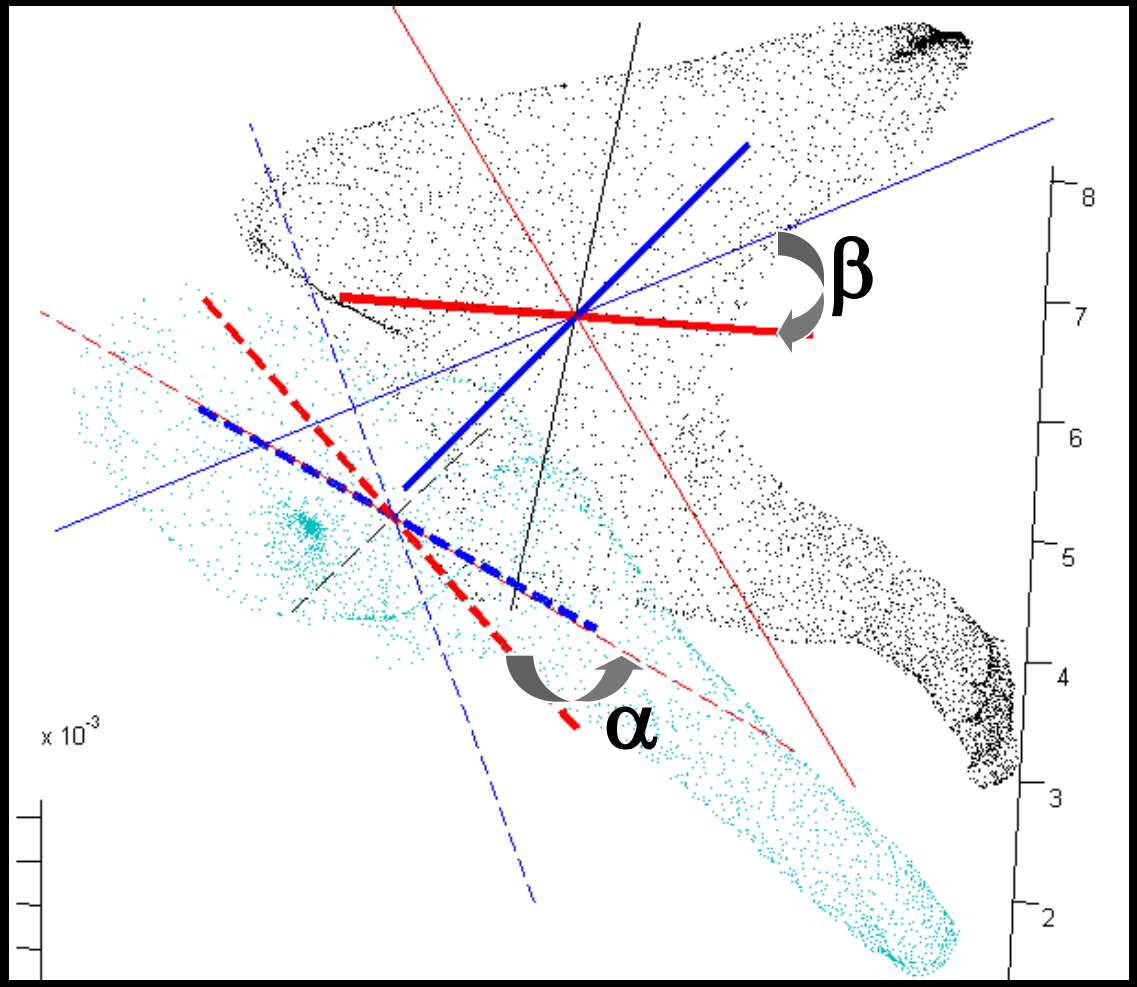


1 kHz, 90 dB SPL



- At low frequencies, the orthotropy of the eardrum boosts the ME gain due to increased peak displacement.

Effects of eardrum orthotropy on ME mechanics



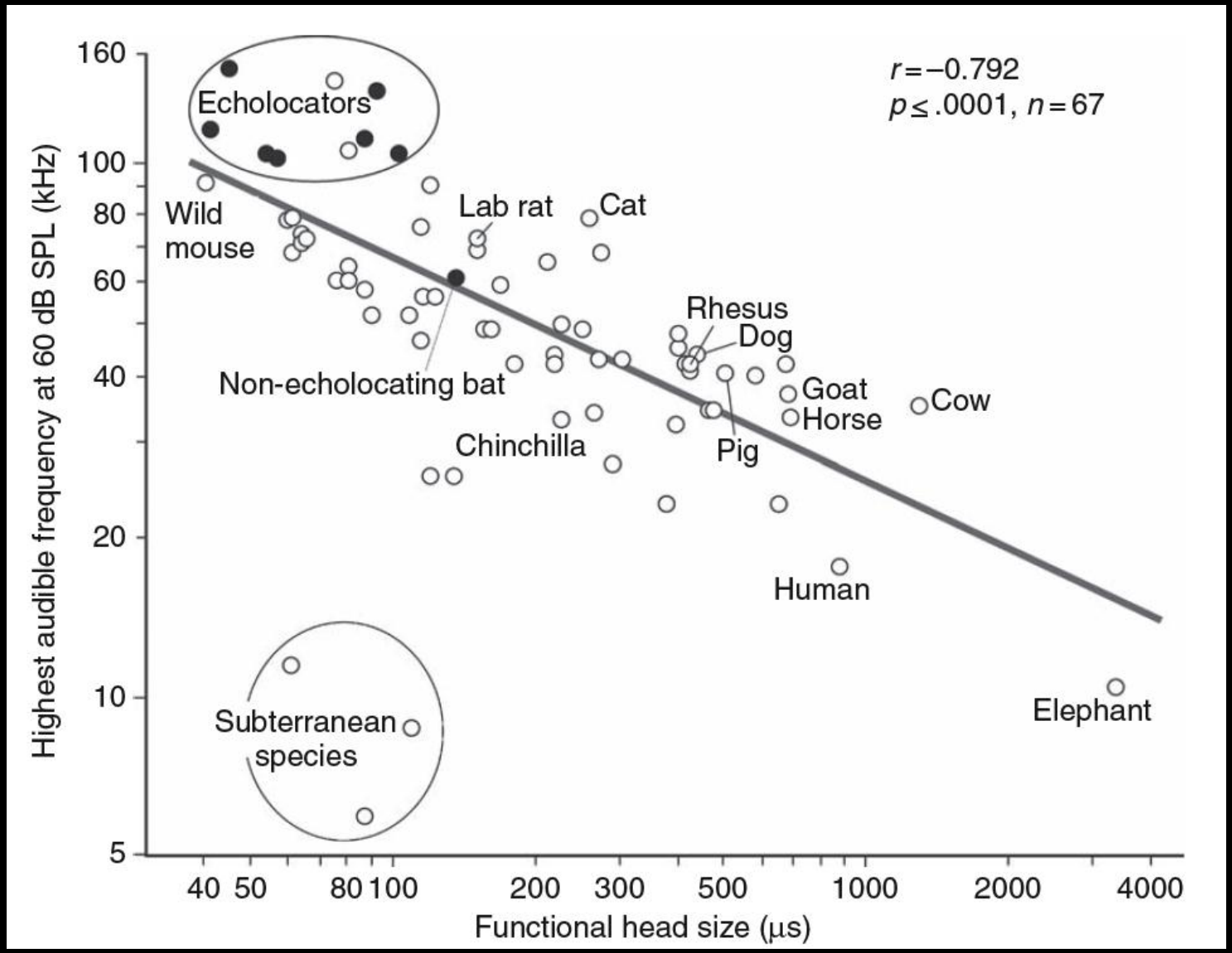
10 kHz, 80 dB SPL

α: 54 ➡ 2
β: 30 ➡ 26
γ: 27 ➡ 16

Red: isotropic
Blue: orthotropic

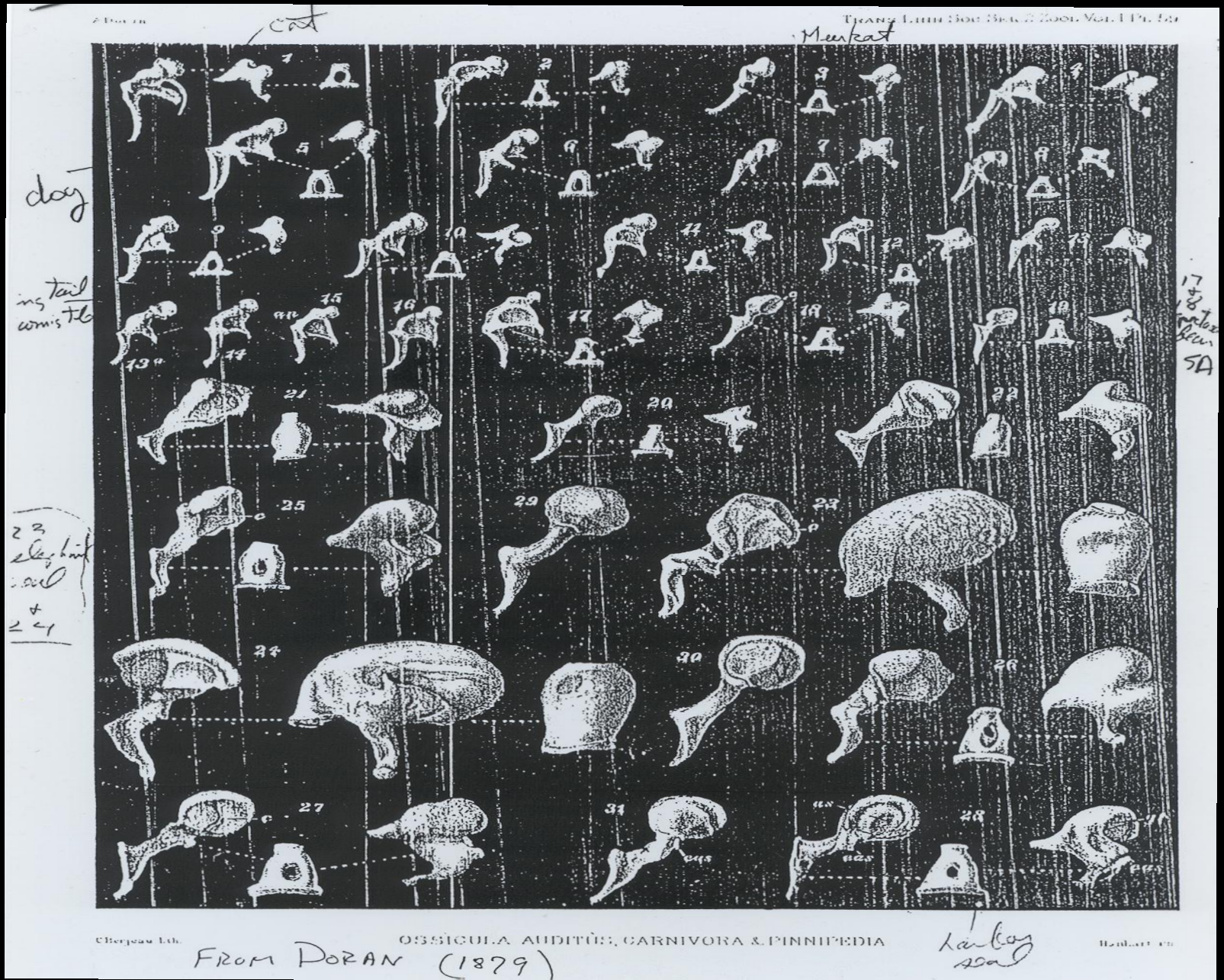
- At high frequencies, the orthotropy of the eardrum makes the rotation axis of the malleus more coincident with its long axis.

Mammals Need High Frequency Hearing for Sound Localization

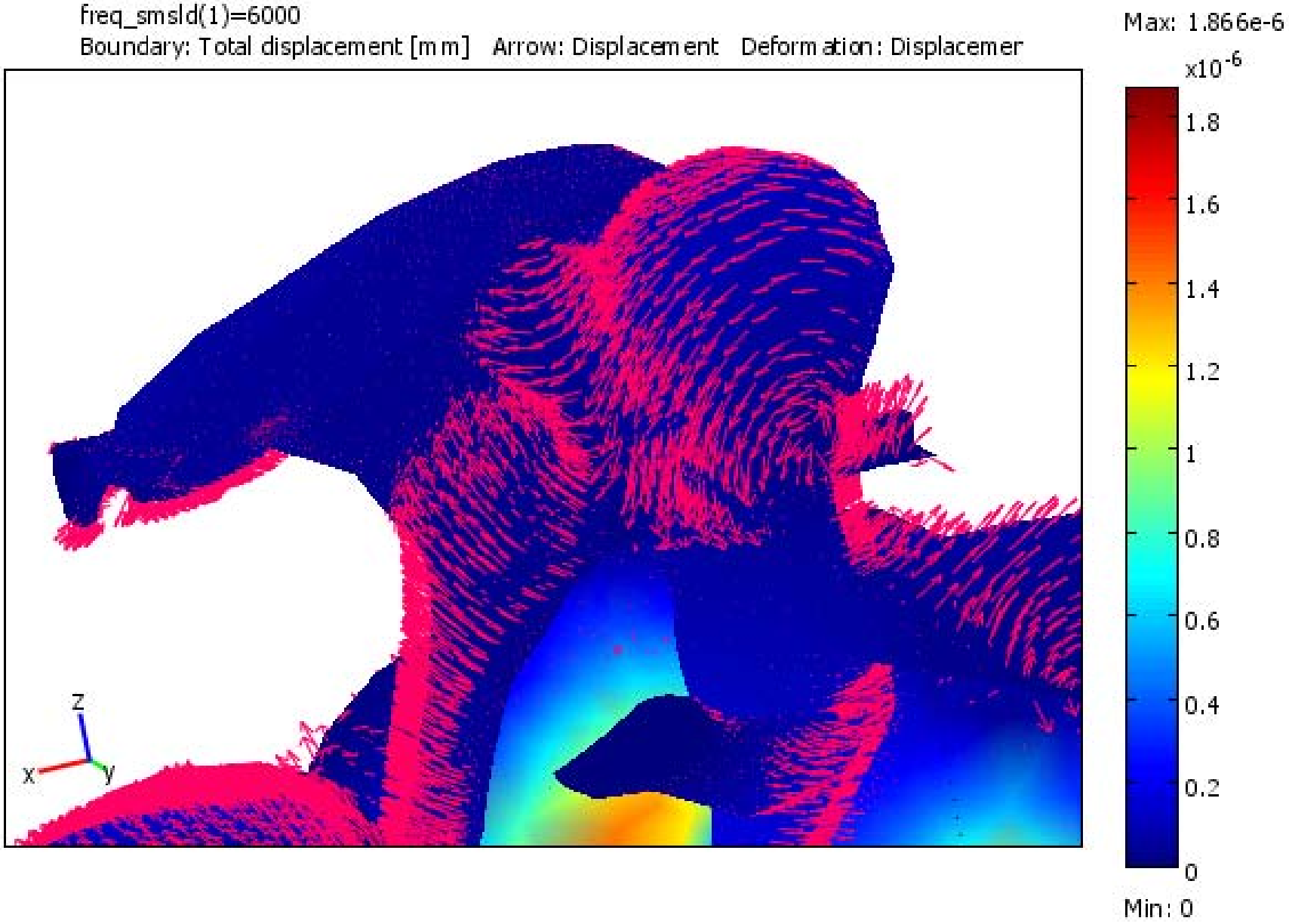


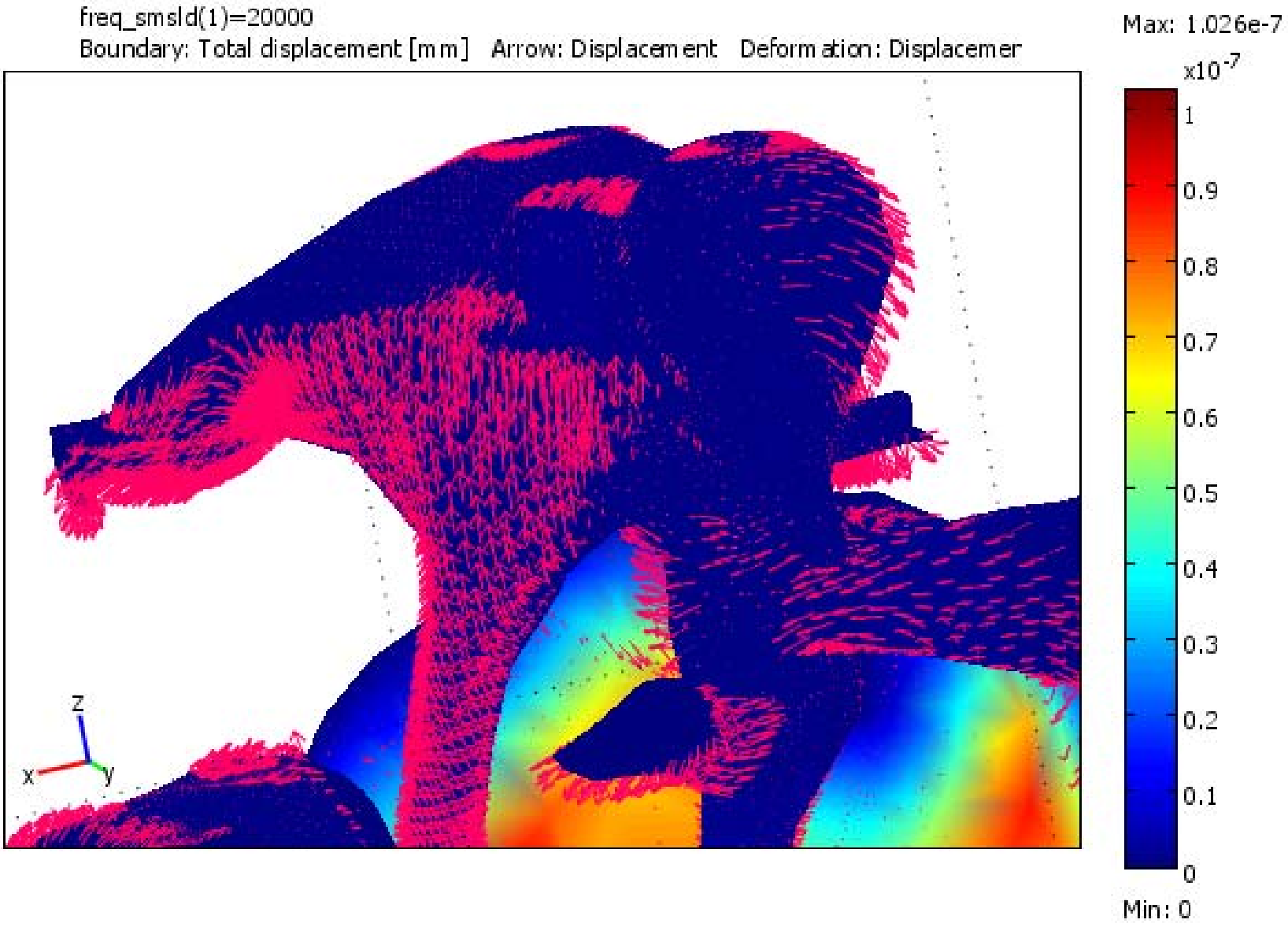
(Masterson et al, 1968; Heffner & Heffner 2008)

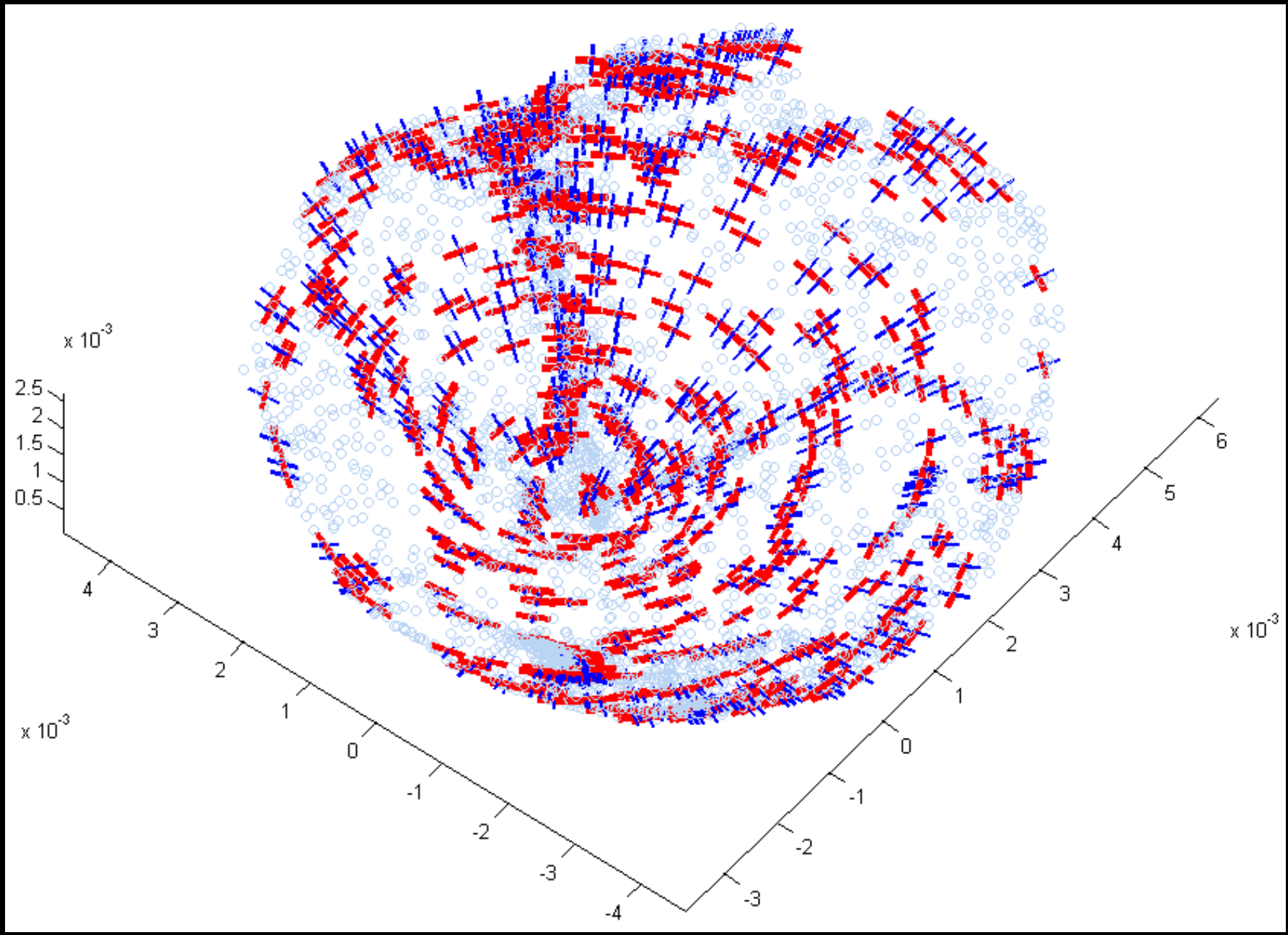
Malleus-Incus Complex Diversity



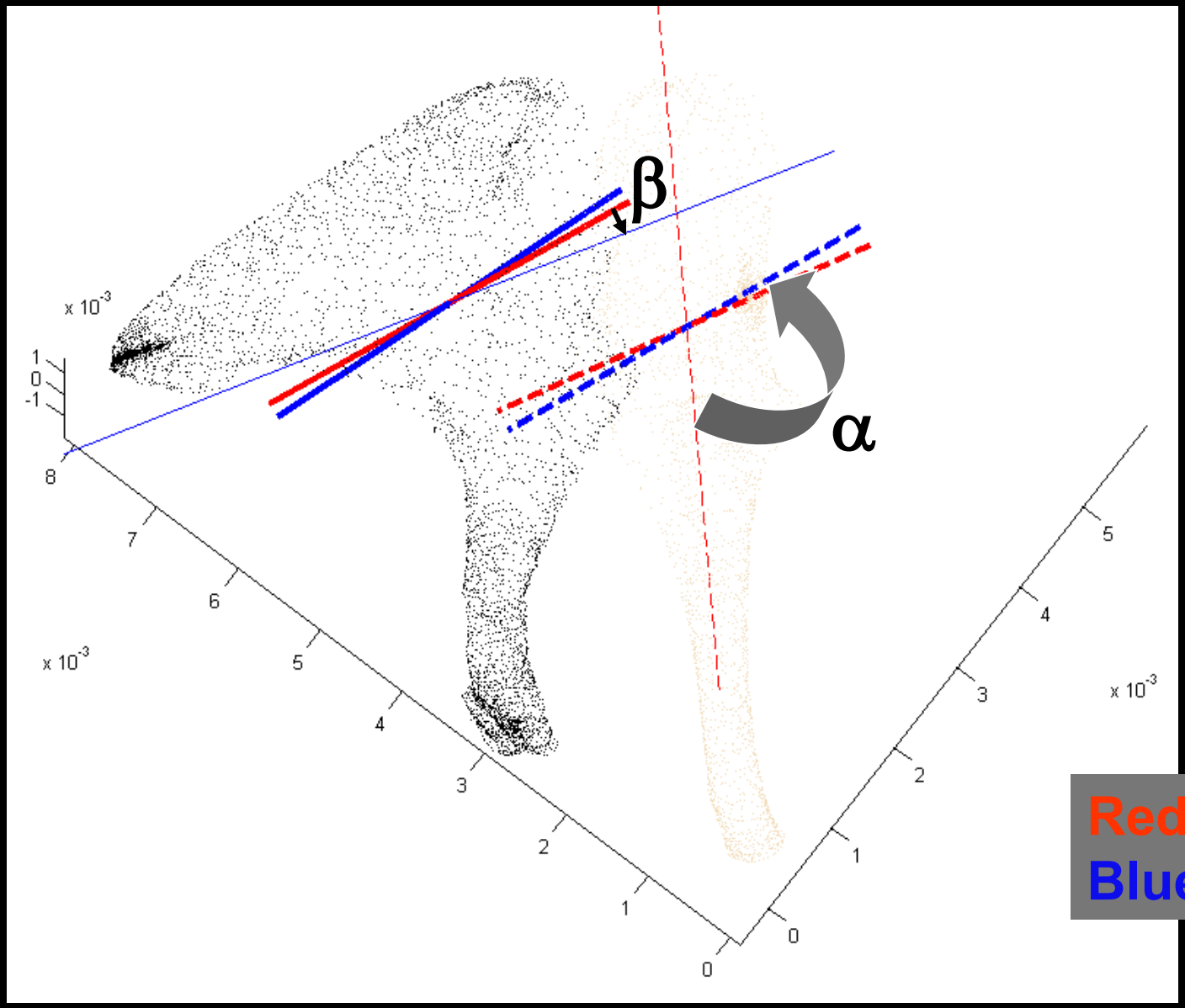
(Doran 1879)


freq_smsld(1)=6000
Boundary: Total displacement [mm] Arrow: Displacement Deformation: Displacemer
Max: 1.866e-6
x10-6
1.8
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
Min: 0
z
x
y


freq_smsld(1)=20000
Boundary: Total displacement [mm] Arrow: Displacement Deformation: Displacemer
Max: 1.026e-7
x10-7
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
Min: 0
z
x
y


x 10^-3
2.5
2
1.5
1
0.5
4
3
2
1
0
-1
-2
-3
-4
x 10^-3
6
5
4
3
2
1
0
-1
-2
-3
x 10^-3

100 Hz, 80 dB SPL



α: 74 → 71

β: 10 → 15

γ: 16 → 20

Red: isotropic

Blue: orthotropic