# *In vivo* quantification of diaphragm viscoelasticity by guided shear wave analysis.

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## RATIONALE

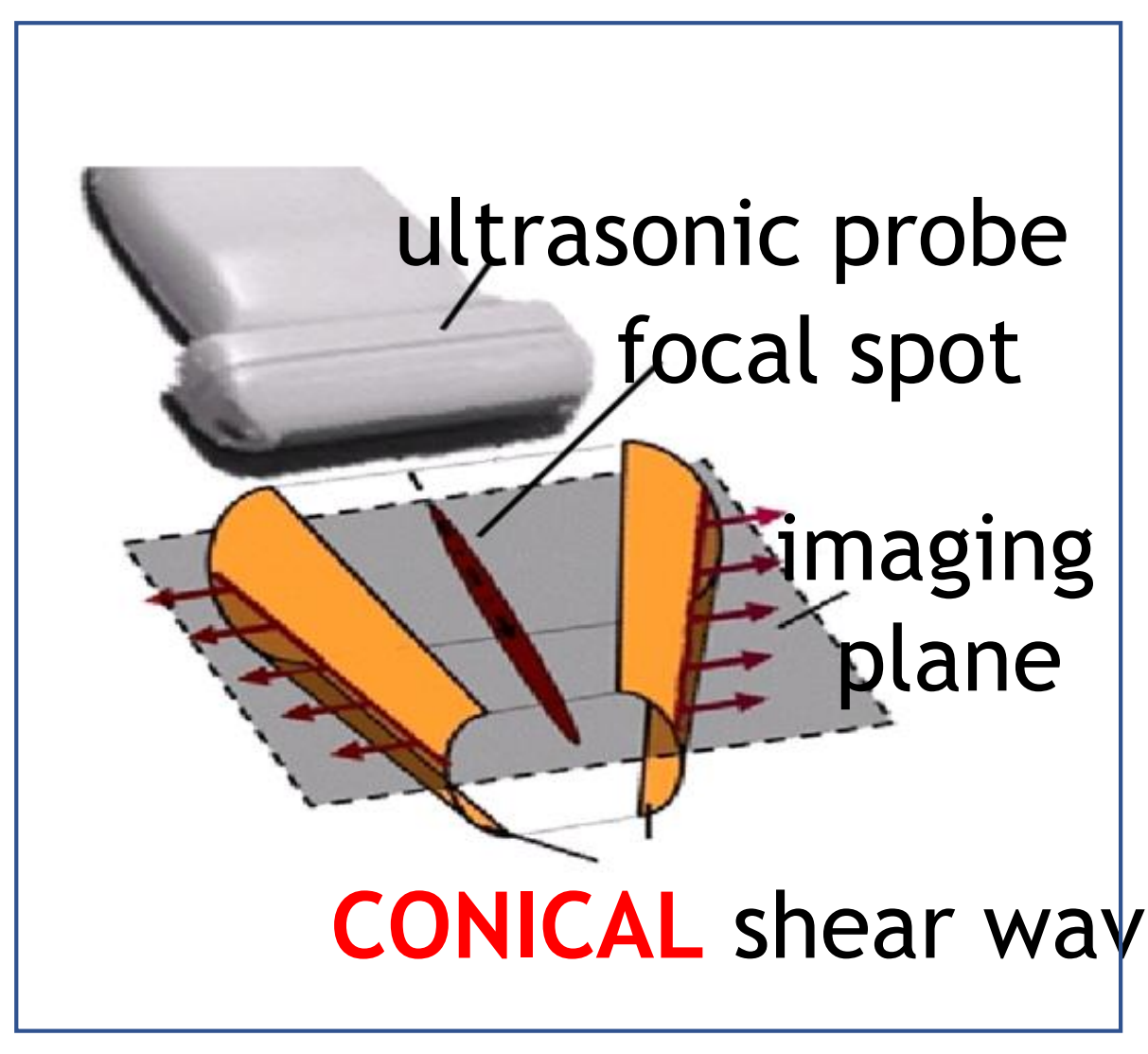
The diaphragm is the main respiratory muscle. Assessing its function is of primary importance in various clinical settings. Shear wave (SW) elastography can be used to as a surrogate to transdiaphragmatic pressure, both in healthy and subjects[a] and critically ill patients[b]. However, diaphragm mechanical properties such as viscosity could provide valuable information about diaphragm function. SW elastography has been used in a variety of biological tissue to estimate their mechanical properties. Because diaphragm thickness is relatively small (h ≈ 2mm), shear waves are very likely to be guided. This phenomenon occurs when the shear waves wavelengths happen to be greater than the tissue thickness. In this work, we used the Supersonic Shear Imaging (SSI) technique to better understand shear wave propagation in the diaphragm. A dispersion analysis was performed to quantify diaphragm viscoelasticity.

## METHODS

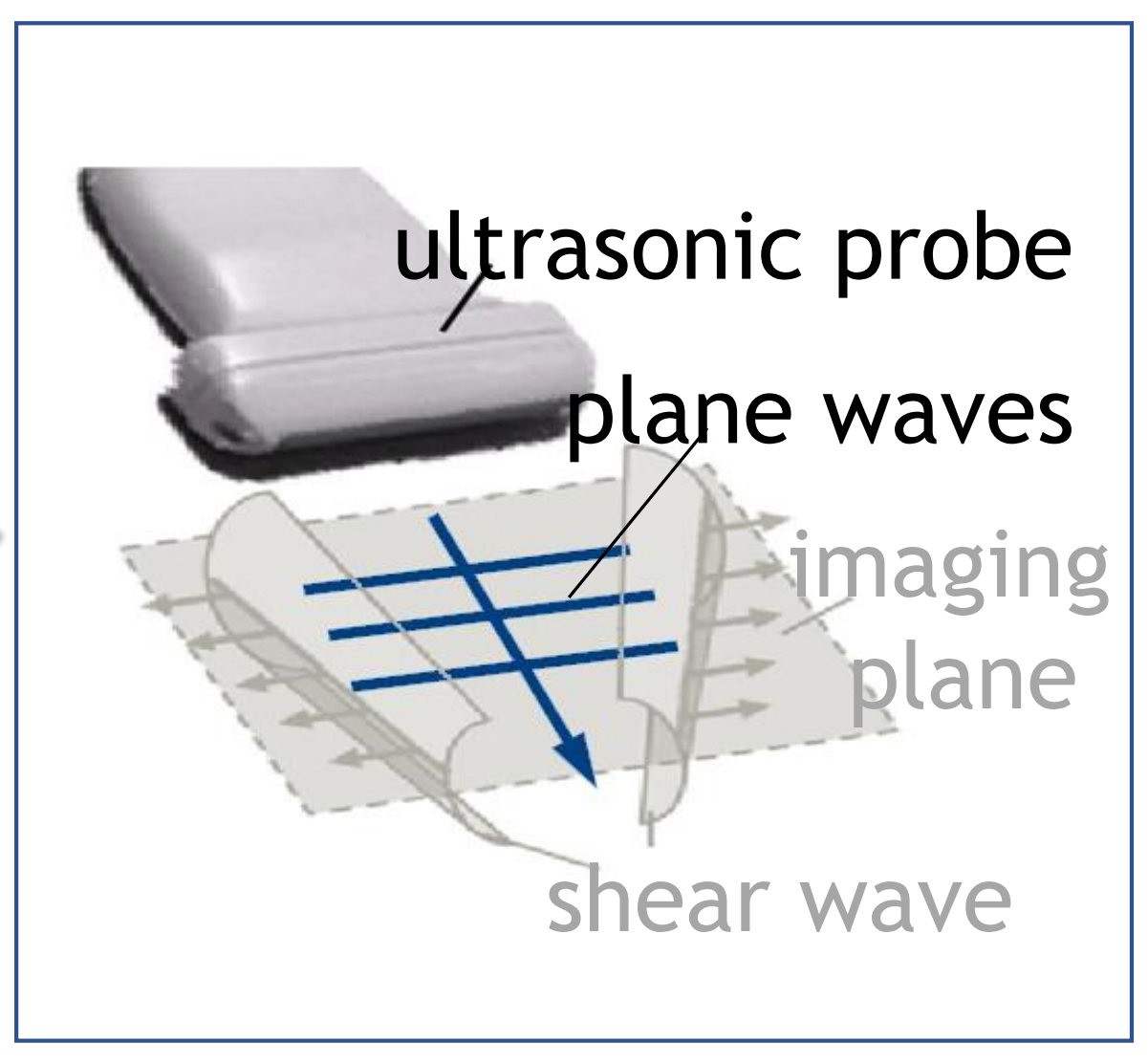
### *Experiments*

***In vivo*** acquisitions in healthy subject with the SSI

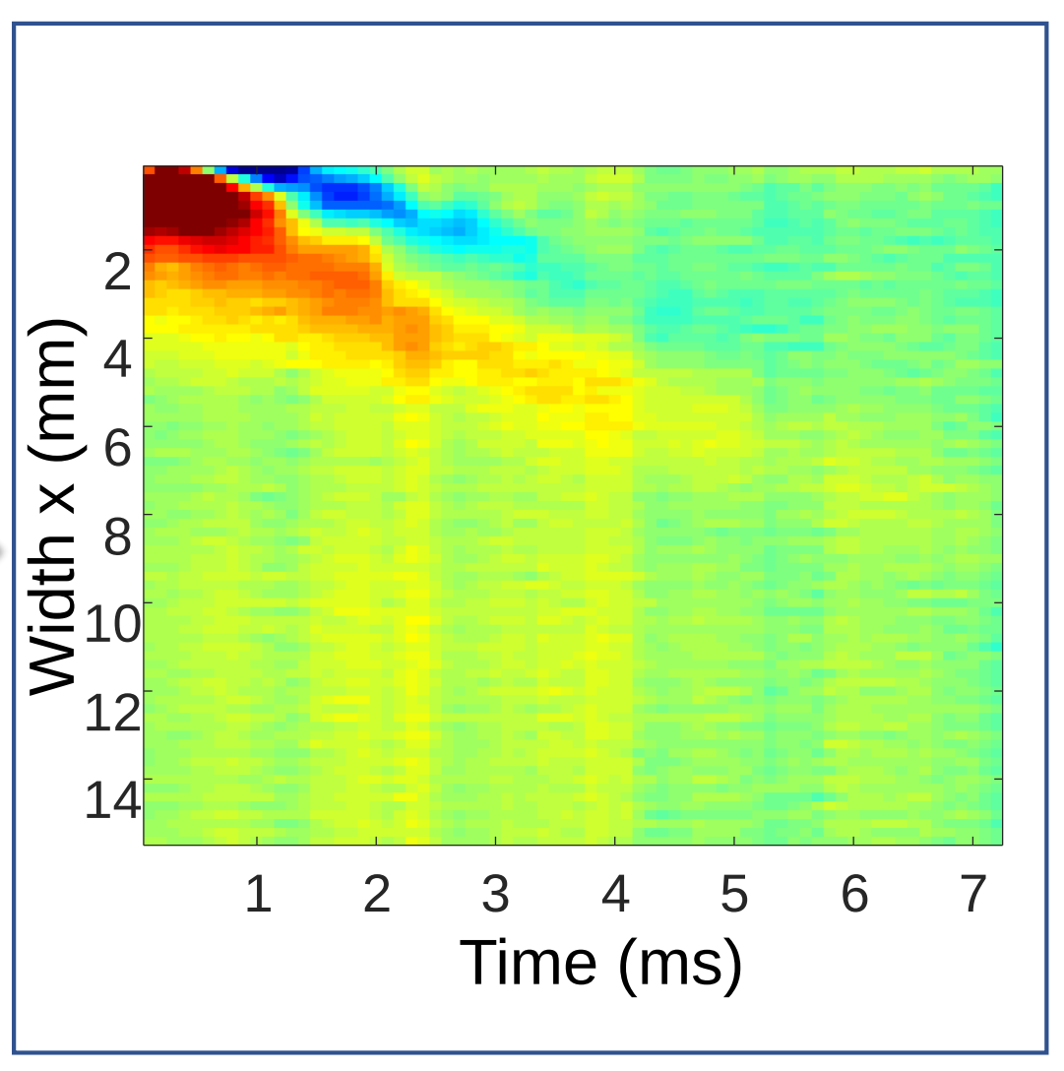
Aixplorer Ultimate and SL15-4 (7.5 MHz)



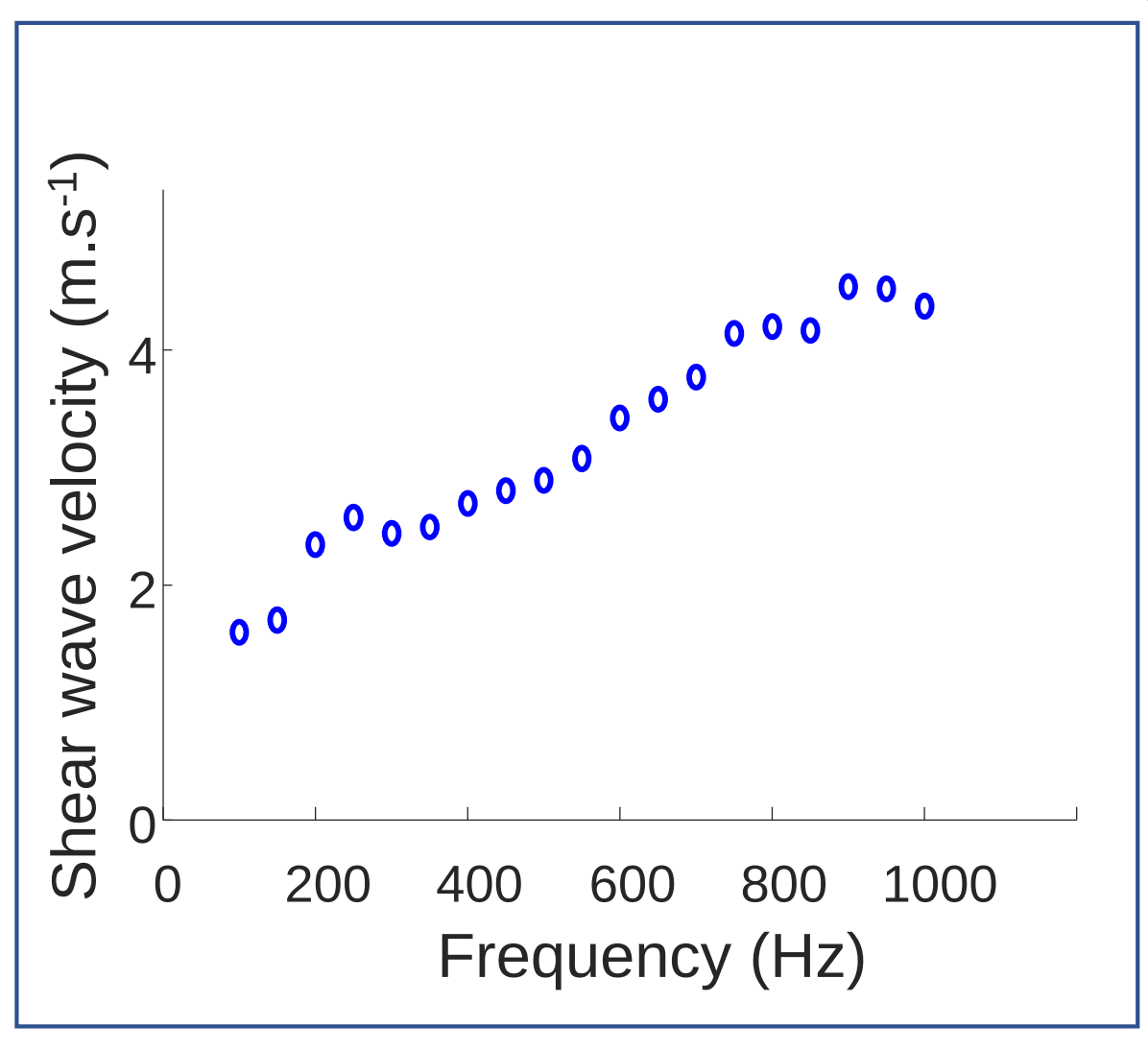
Generation of a transient shear wave using the **ultrasonic radiation force.**



**Ultrafast imaging** of the shear wave propagation (8000 frames.s$^{-1}$).



FFT2D



shear wave speed dispersion curve

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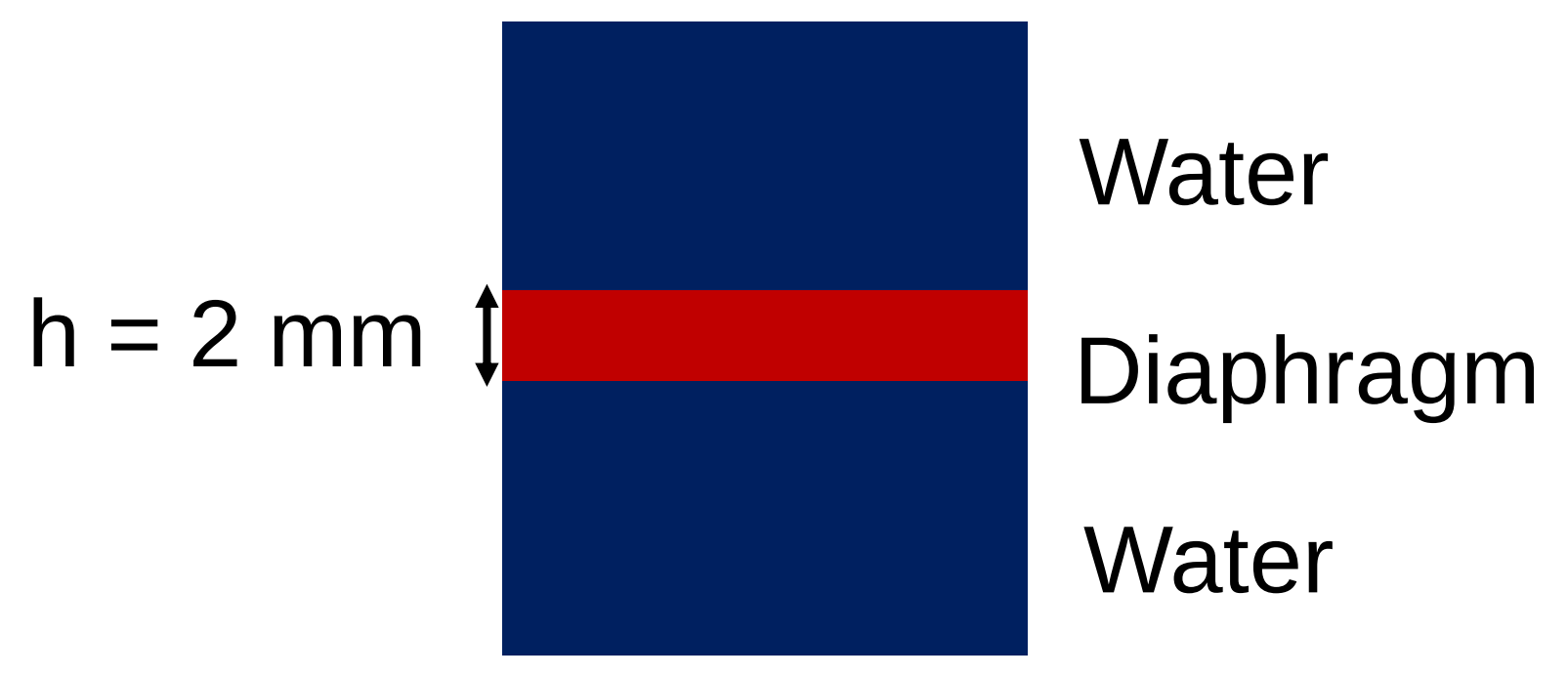
### *Simulations*

Simulations performed using the SimSonic Matlab Toolbox



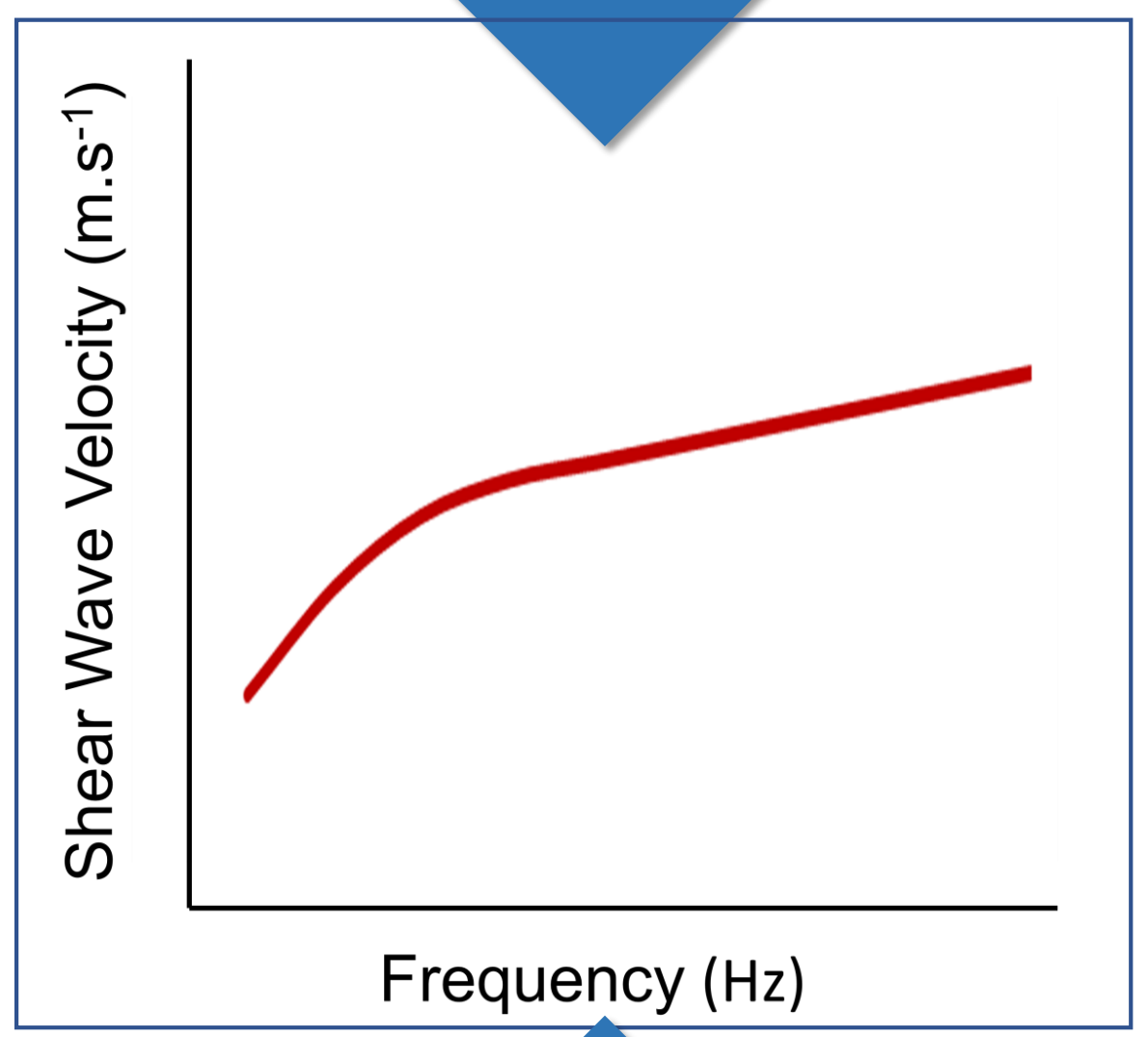
The diaphragm was simulated as an isotropic elastic plate immerged in water. Elastic coefficients of the Christoffel tensor for the diaphragm were as follow:

$c_{11} = c_{33} = 2.3716$ GPa

$c_{13} = 2.3715$ GPa

$c_{55} = 19.9808$ kPa

Diaphragm mechanical properties were retrieved by fitting an appropriate propagation model to the phase velocity dispersion curve (Voigt's model)[c] and compared to *in vivo* acquisition.



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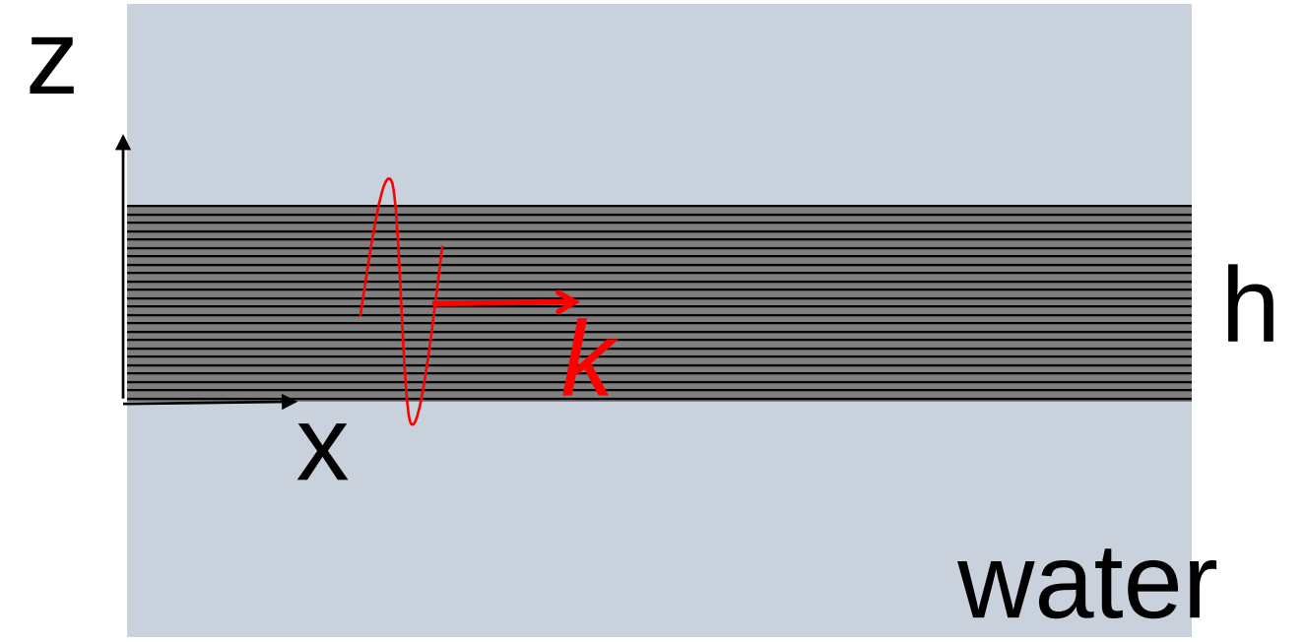
### *Analytical model*



*Anti-symmetric quasi-Lamb modes[c]:*

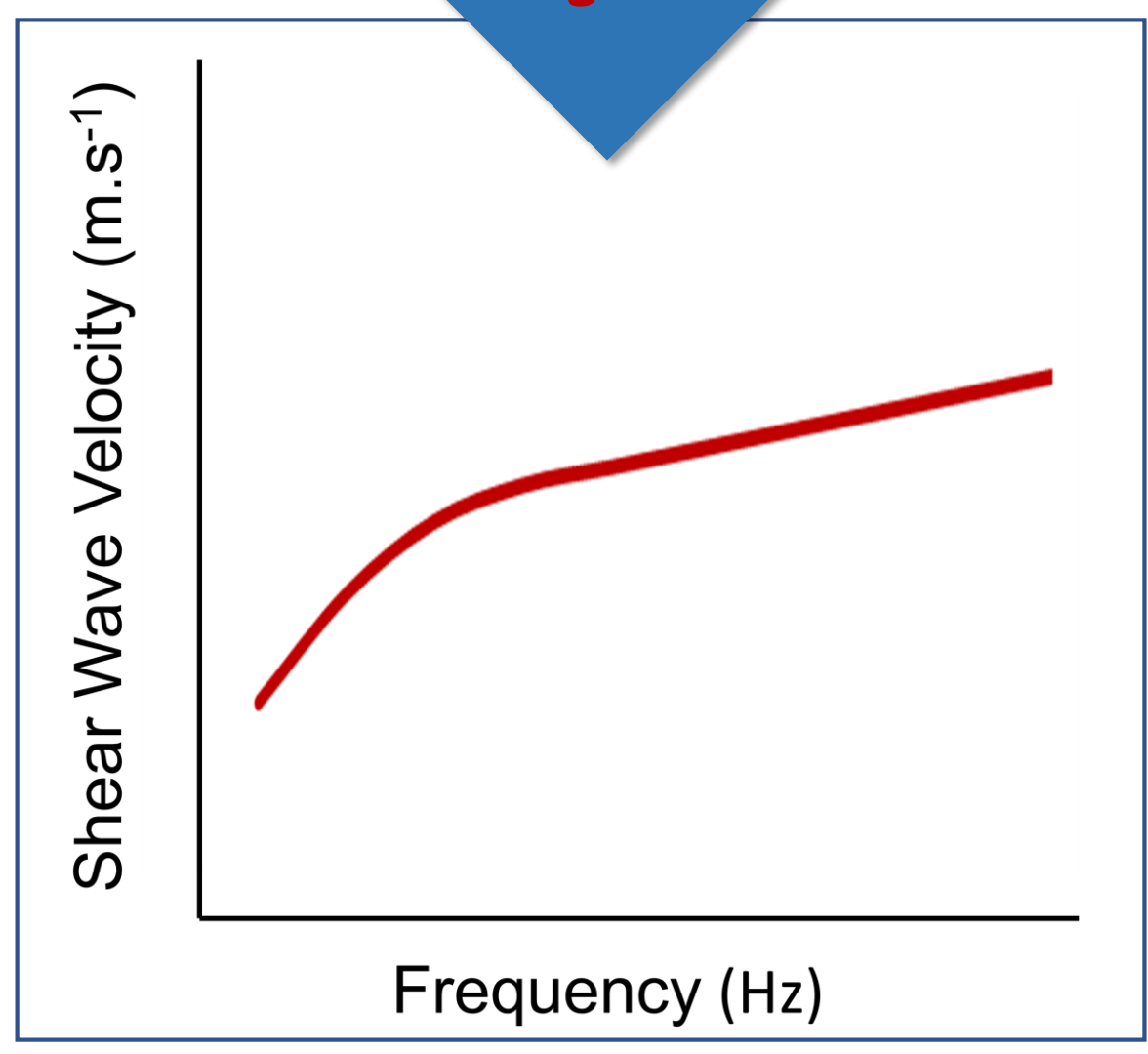
$$\boxed{\frac{G_p H_m}{G_m H_p} - \frac{\tan(k_p h/2)}{\tan(k_m h/2)} + i\frac{\rho_{liq}\omega^2}{k_{liq}}\frac{\cot(k_p h/2)}{G_m}\left(\frac{H_m}{H_p} - 1\right) = 0}$$

$$H_{p,m} = k + k_{p,m}\left(\frac{\rho\omega^2 - C_{11}k_{p,m}^2 - k^2 C_{55}}{(C_{55}+C_{13})k_{p,m}k}\right) \qquad G_{p,m} = C_{11}k_{p,m} + C_{13}k\left(\frac{\rho\omega^2 - C_{11}k_{p,m}^2 - k^2 C_{55}}{(C_{55}+C_{13})k_{p,m}k}\right)$$

$$k_{p,m}^2 = \frac{k^2}{2}\left(-B \pm \sqrt{B^2 - 4D}\right)$$

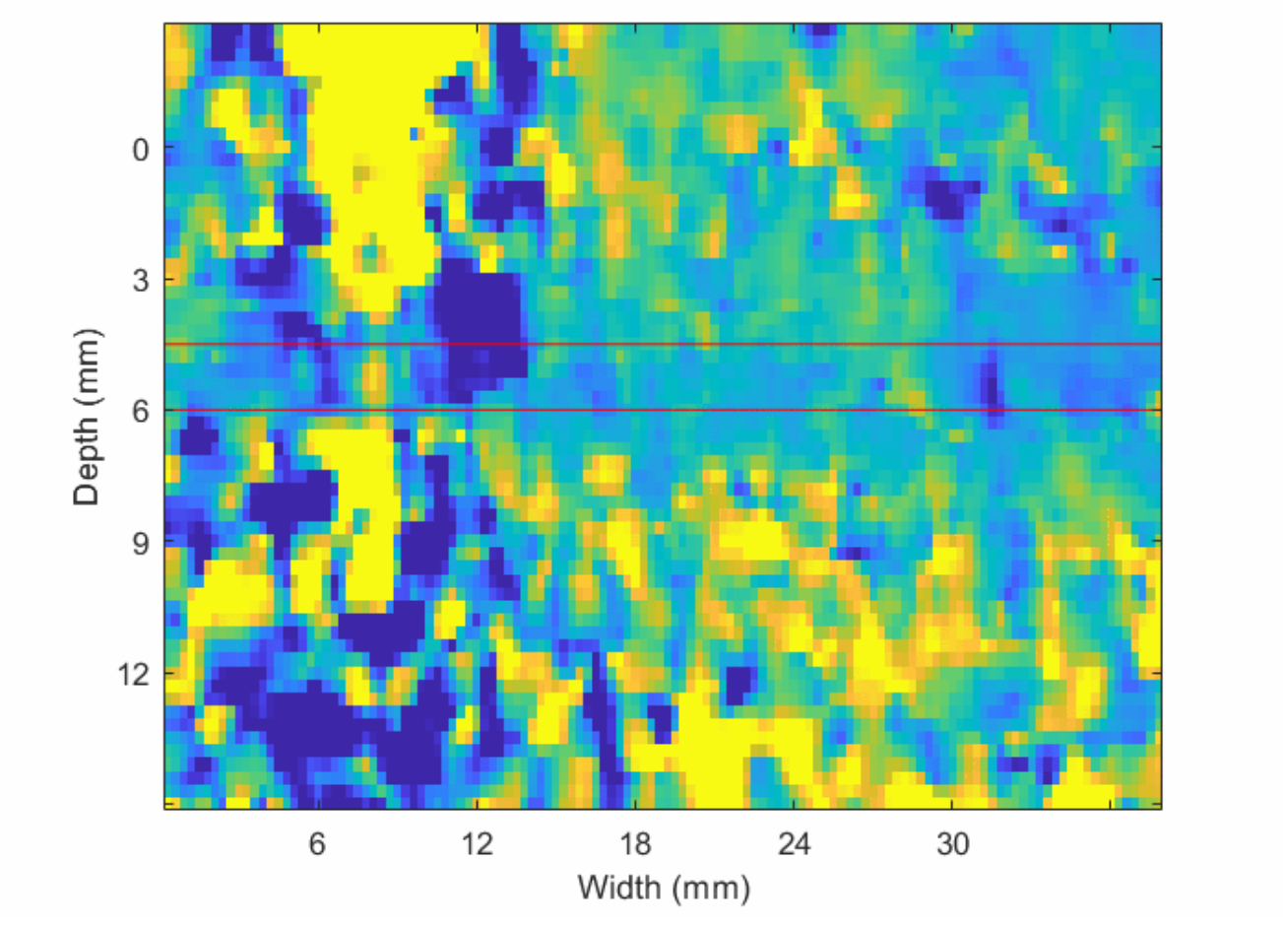
$$B = \frac{-(C_{55}+C_{13})^2 - (\rho\omega^2/k^2)(C_{55}+C_{11})}{C_{11}C_{55}} + \frac{C_{11}.C_{33} + C_{55}^2}{C_{11}C_{55}} \qquad D = \frac{\rho\omega^2}{k^2}\frac{\rho\omega^2/k^2 - C_{33}}{C_{11}C_{55}} - \frac{\rho\omega^2}{k^2}\frac{1}{C_{11}} + \frac{C_{33}}{C_{11}}$$

Quasi-Lamb wave propagation in plate of elastic constants: **$C_{11}$ ; $C_{33}$ ; $C_{13}$ & $C_{55}$**

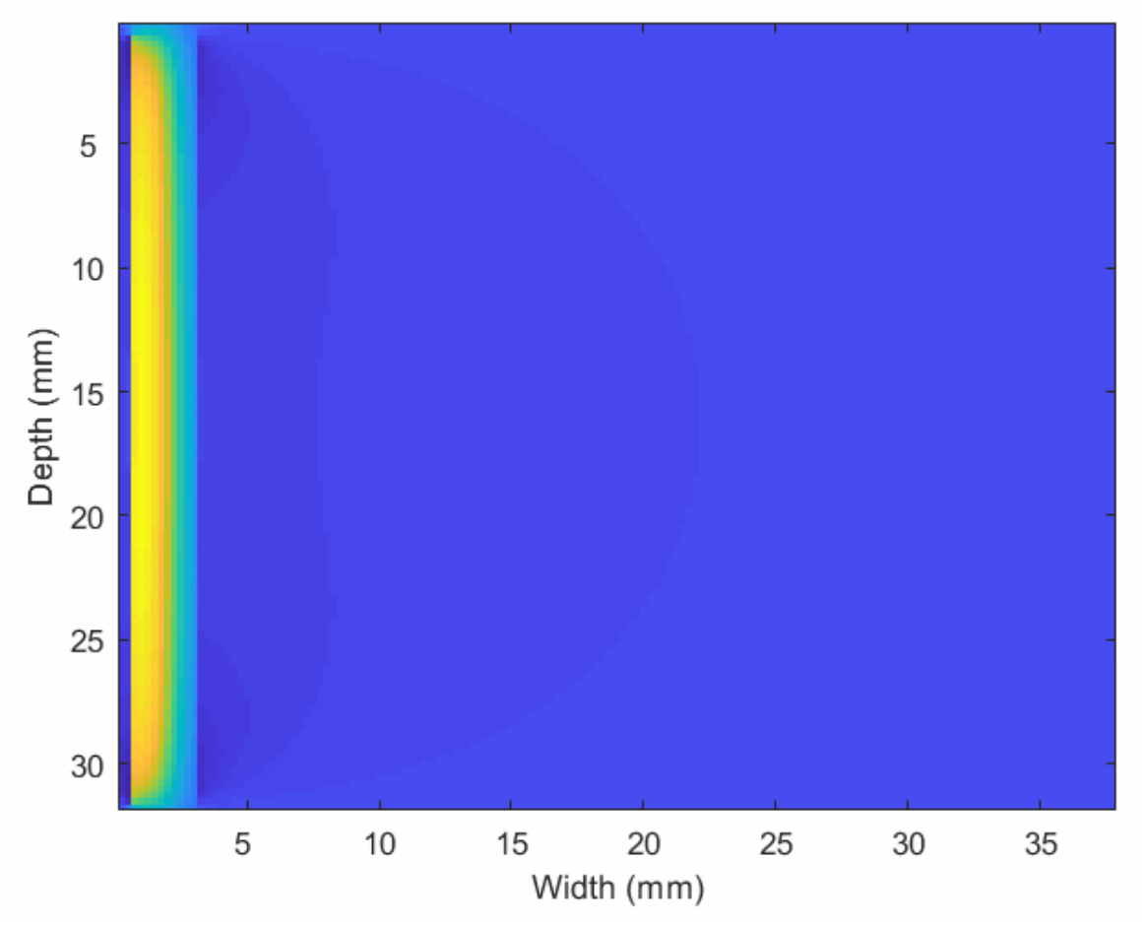


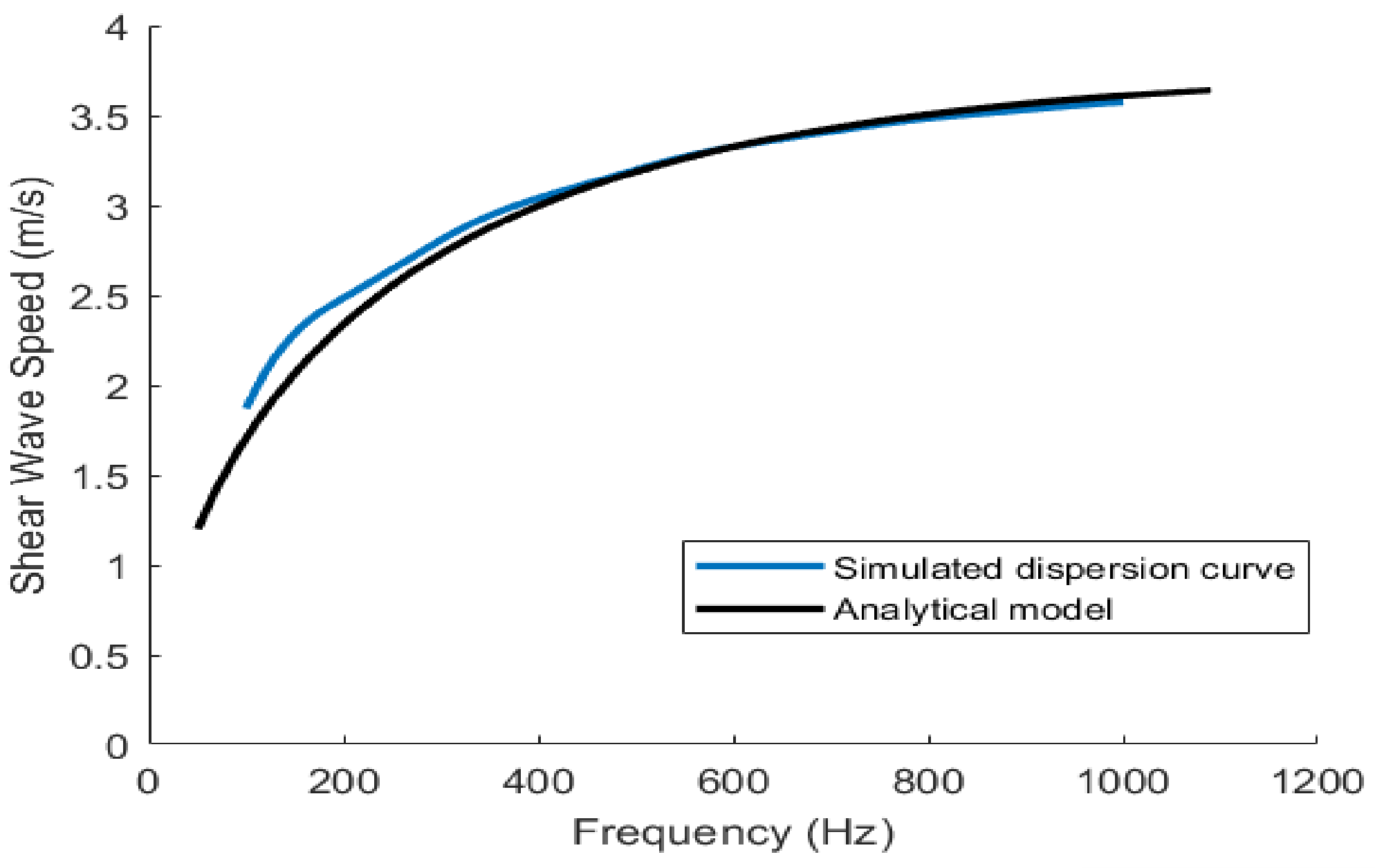
## RESULTS

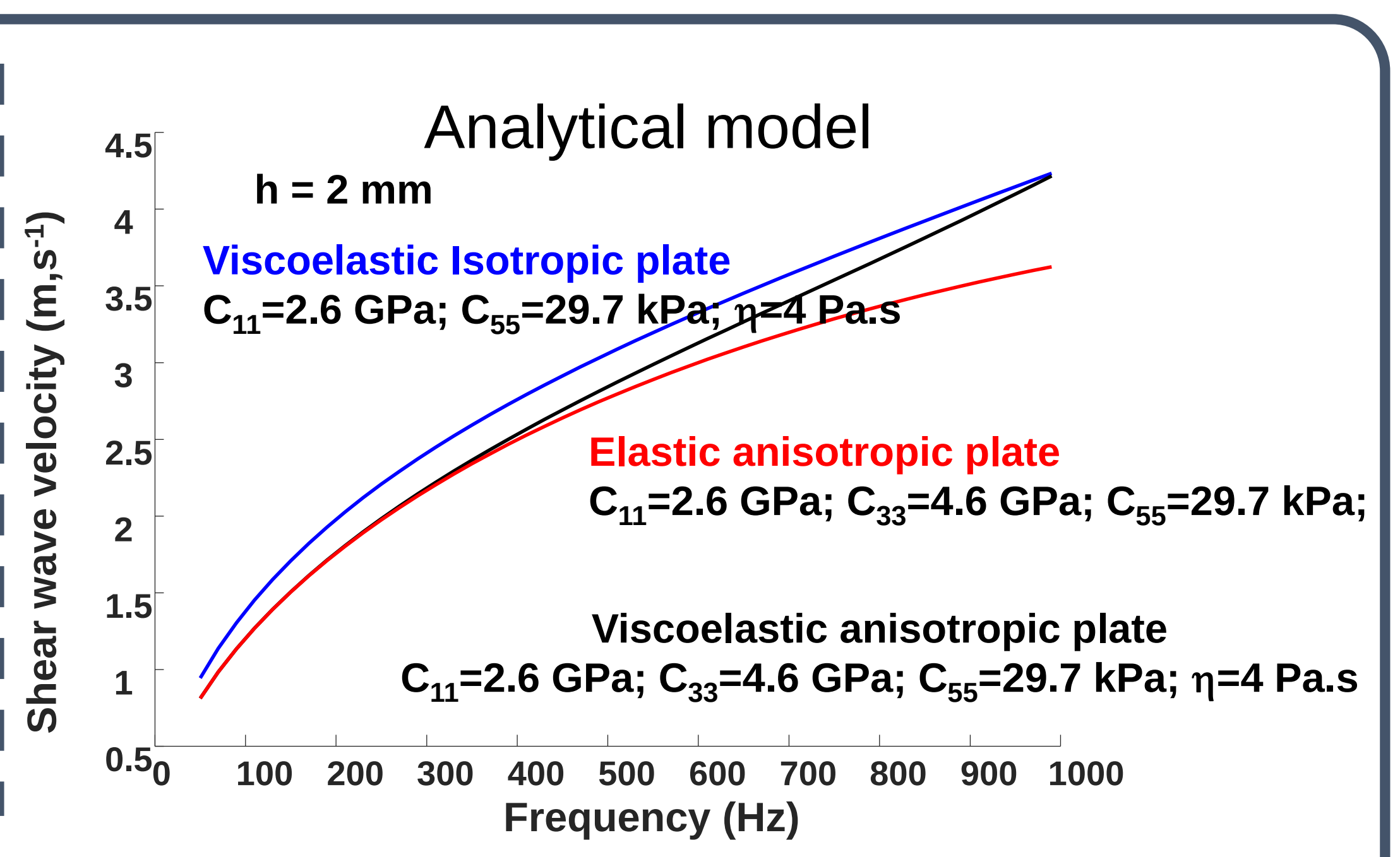
*In vivo* experiment



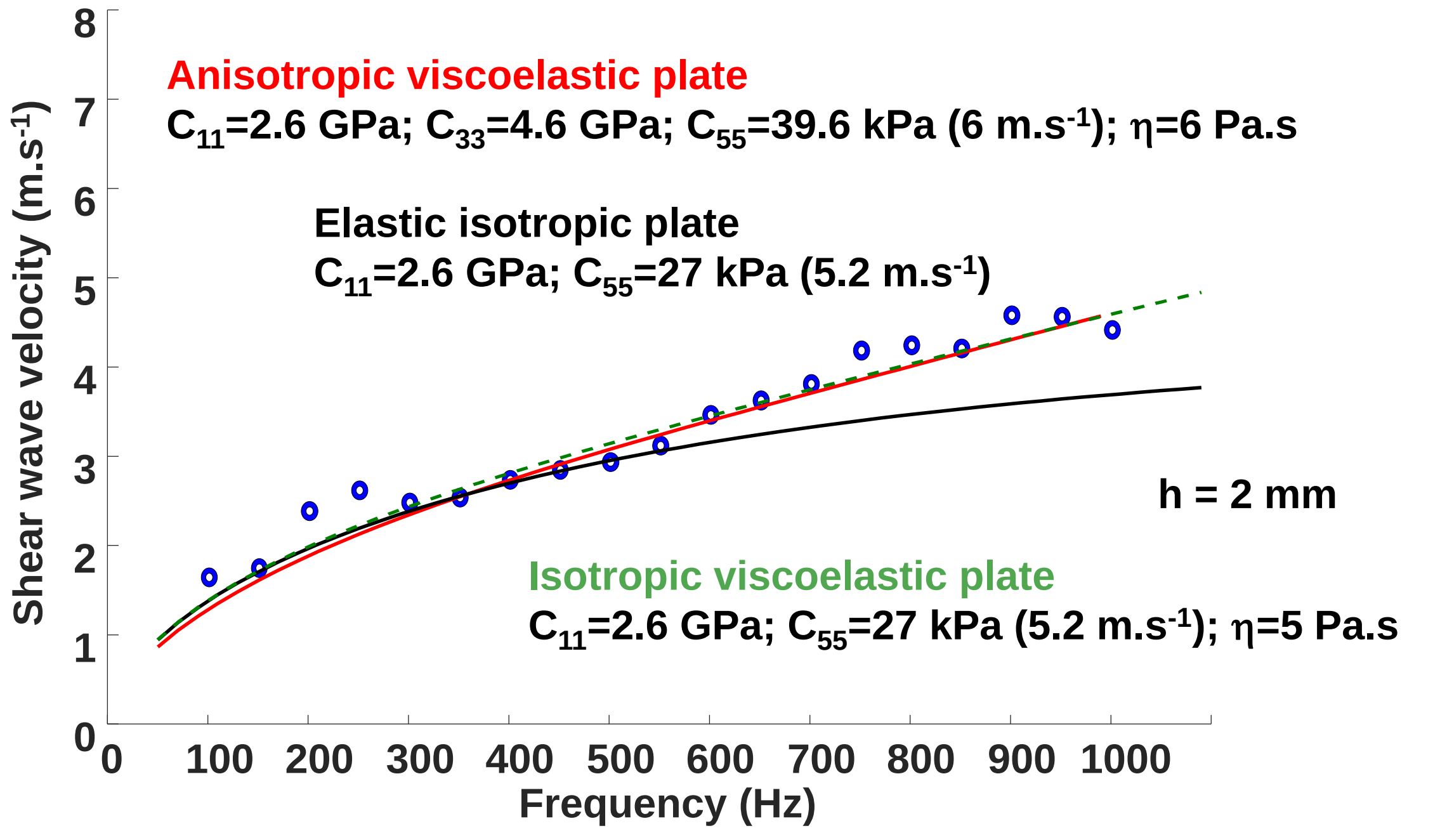
Simulation







A very good agreement was found between the analytical model and the simulation. The increase in SW speed with the increase in frequency corresponds to the lowest flexural model of the plate parallel to the fibers. The increase in SW speed with SW frequency indicates that SW may be guided within the diaphragm. *In vivo* Experimental data (blue doted line) are well predicted by both analytical model: anisotropic viscoelastic plate and isotropic viscoelastic plate.



## CONCLUSION

Our results support previous findings regarding the guidance of SW in confined tissues. It also highlights the potential of the SSI technique for the *in vivo* assessment of diaphragm viscoelasticity, also during breathing. Further works are being developed to establish the proper guided model for the SW propagation. This includes analytical modelling + simulation with proper boundary conditions.

**References:**

[a] Bachasson et al. Ultrafast Ultrasound Imaging Grants Alternate Methods for Assessing Diaphragm Function. In 2018 IEEE International Ultrasonics Symposium (IUS) (pp. 1-4). IEEE.

[b] Poulard et al. Ultrasound shear wave elastography for assessing diaphragm function within the intensive care unit. In 2019 IEEE International Ultrasonics Symposium (IUS) (pp. 966-969). IEEE.

[c] Brum et al. In vivo evaluation of the elastic anisotropy of the human Achilles tendon using shear wave dispersion analysis. Physics in Medicine & Biology, 59(3), 505.

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