ESTIMATING CEREBRAL MECHANICAL PROPERTIES NON-INVASIVELY THROUGH THE USE OF TISSUE PULSATIONS IN THE HUMAN BRAIN

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Introduction

The mechanical properties of in vivo brain tissue remain very poorly characterized. Ex vivo measurements often provide only a poor estimate of in vivo properties. These properties are, however, critical in understanding the brain's behavior in both normal and pathological states. The use of ultrasound, via the Transcranial Tissue Doppler method (TCTD), has received new interest recently, as the measurements are well tolerated, even by patients, and are quick and cheap to acquire [1]. Brain tissue pulsations (BTP) are measured through the forehead and can be recorded simultaneously with many other physiological variables.

Theory

The brain is assumed to comprise a coupled solid-fluid system with a single fluid compartment. Hence:

$$G\nabla^2\mathbf{w} + \frac{G}{1-2\nu}\nabla(\nabla.\mathbf{w}) - \alpha\nabla.p\mathbf{I} = \rho_s\frac{\partial^2\mathbf{w}}{\partial t^2}$$

$$\nabla.\left(\frac{\kappa}{\mu}\nabla p\right) = \frac{\partial}{\partial t}\left(\alpha\nabla.\mathbf{w} + \frac{p}{Q}\right)$$

where the solid is assumed to be a linear, isotropic material with density ρ_s, shear modulus G and Poisson ratio ν. The fluid is taken to follow Darcy's law with permeability κ and viscosity μ, the Biot-Willis coefficient is denoted by α and specific storage by Q. The fluid has pressure p and the solid displacement $\mathbf{w}$. We assume a composite solution:

$$w(r,t) = w_0(r) + \hat{w}_1(r)e^{i\omega t}$$

$$p(r,t) = p_0(r) + \hat{p}_1(r)e^{i\omega t}$$

Hence:

$$\frac{d^2\hat{w}_1}{dr^2} + \frac{2}{r}\frac{d\hat{w}_1}{dr} + \hat{w}_1\left[\frac{\rho_s\omega^2}{E^*} - \frac{1}{(1-\nu)}\frac{1}{r^2}\right] = \frac{\alpha}{E^*}\frac{1}{r^2}\frac{d(r^2\hat{p}_1)}{dr}$$

$$\frac{d^2\hat{p}_1}{dr^2} + \frac{2}{r}\frac{d\hat{p}_1}{dr} - \hat{p}_1\left(\frac{i\omega\mu}{\kappa Q}\right) = \left(\frac{\alpha i\omega\mu}{\kappa}\right)\frac{1}{r^2}\frac{d(r^2\hat{w}_1)}{dr}$$

The solution requires four boundary conditions. At the brain surface, we assume zero displacement and unit non-dimensional amplitude pressure. At the inner (ventricle) surface, where $r' = \delta$, we assume zero fluid flux and a mixed boundary condition for displacement.

Experimental data

BTP recordings were obtained from 20 volunteers at rest [1]. Recordings were obtained using a Brain Tissue Velocimetry (Brain TV) TCTD prototype (Nihon Kohden, Japan). This is equipped with a standard 2 MHz TCD probe, placed on the forehead approximately 1 cm above the orbit on the right side. Synchronous BP readings were obtained using a finger-cuff Finometer system. Velocity was integrated over time to obtain a BTP signal representing tissue displacement at 33 depths (22-86 mm). Good quality signals were recorded for the first 19 depths in all subjects. The data were converted to transfer function form to give an ensemble-averaged frequency response at the fundamental harmonic as a function of depth, Figure 1. There is significant variability between individual subjects, but a clear trend of increasing magnitude with depth.

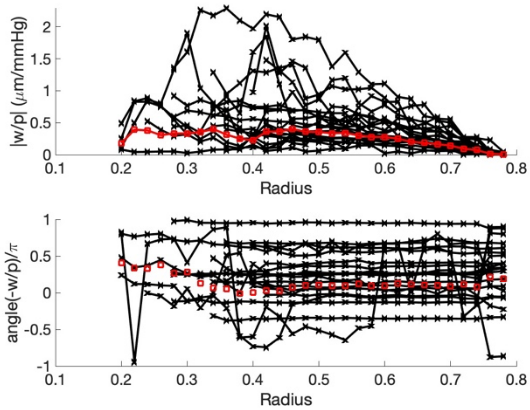

Figure 1: Transfer function (top: gain; bottom: phase): individual subjects (black); population-averaged (red).

Results

Using a simple optimization method based on RMSE, we calculated the parameter values that yield the best fit to the population-averaged data (fitting only four key parameters). To ensure convergence, a wide range of the parameter space is explored. The parameter values ($E =$ 17.6 kPa; κ/μ = 8.73 x 10^{-7} m^3s/kg; Q = 4,570 kg/m.s; $\nu = 0.499$) are in line with existing literature.

Conclusions

A new methodology for estimating cerebral mechanical parameters is presented using BTP and preliminary results show promise. Future work will focus on more detailed analysis and the estimation of parameters under different conditions and for individual subjects.

References

1. Turner P et al. Ultrasound Med Biol. 2020;46:3268-78.

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