ESTIMATING THE MATERIAL PROPERTIES OF BRAIN TISSUE AT IMPACT FREQUENCIES: A CURVE-FITTING SOLUTION.

Samuel A. Lippert and Michele J. Grimm

Department of Biomedical Engineering
Wayne State University
Detroit, MI 48201

INTRODUCTION

The increasing importance of brain tissue mechanical properties, as a result of new computer models of the head and brain, cannot be understated. Current modeling efforts include, but are not limited to, surgical simulations and models of closed head injury . Unfortunately, given the frequency and strain [1, 2] dependence of brain tissue, the properties that are appropriate for one model are not necessarily appropriate for another. This being the case, it is important that brain tissue be characterized over as broad a frequency range as is possible.

Complex Young's moduli (obtained via compression testing) and complex shear moduli have been published for a variety of frequencies, ranging from 0.01Hz through 350Hz, and at a variety of strain magnitudes [1, 3-11]. Recently testing of brain tissue in the 100kHz to 10MHz range was completed using an ultrasonic technique [12]. All of these results can be found Figure 1.

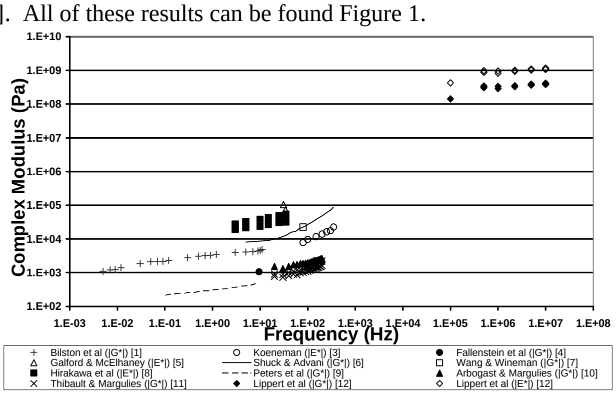

Figure 1: Published complex modulus data.

METHOD

The first step towards a meaningful curve fit requires an understanding of the variation seen in the existing low frequency data.

Tensile Modulus

The existing data for tensile modulus closely approximates an "S" shaped curve, similar to that of many other non-linear visco-elastic materials. The data from Koeneman [3] is the exception. Fallenstein *et al* [4] found that freezing of brain tissue "lowered the storage modulus approximately an order of magnitude and the loss modulus by a factor of three." Given the relationship between shear modulus and Young's modulus, it stands to reason that a change in the components of the shear modulus should result in an equivalent change in the components of the Young's modulus. In Koeneman's research, the brain tissue was frozen in order to prepare the samples, then thawed before testing [3]. Figure 2 shows how the Koeneman data shifts if the storage modulus (E') is increased by a factor of ten, and the loss modulus (E") is increased by a factor of three. Notice how the estimated data is now in line with the data of the other researchers after the approximate correction is applied.

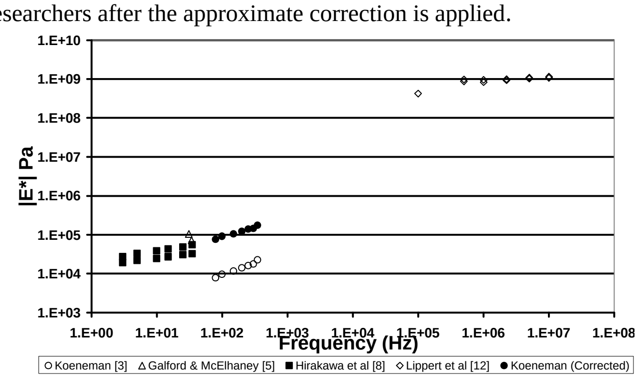

Figure 2: Young's modulus data (Koeneman data adjusted).

Shear Modulus

Returning to Figure 1 to examine shear modulus, it quickly becomes evident that existing shear modulus data at lower frequencies appear in two distinct curves separated by approximately one order of magnitude. Either of these data groups could be reasonably used in the curve fit; however, given the separation, it does not make sense to utilize both. Bilston *et al* [1] along with varying frequency, also performed experiments involving variations in maximum strain. It was found that strains above approximately 0.1% substantially reduced the observed modulus. Examining the experimental procedures for the existing data, it was found that the data with the higher moduli were taken at around 0.1% strain, and the data with the lower moduli were taken at strains of 2.5% and higher. As ultrasound produces strains much lower than 0.1%, the group one data was useed in the curve fit.

Curve Fit Details

In all cases, the curve fits were performed using the combined results for white and gray matter. This was due to the fact that all useable low frequency data, with the exception of the data obtained by Hirakawa *et al* [8], was available only for combined tissue.

Curve fitting was done utilizing NCSS, a statistical software package. For each curve fit, possible equations were evaluated based on the criteria that the curve must be continuous, must not cross y=0, should be monotonic, must have an R-squared near one, should be undefined for negative x and should have a low chi-squared.

For both moduli, six separate curve fits were performed between the average values obtained by us and those obtained by prior researchers. For each fit, the data for one frequency was not used in generating the curve. The estimated equation was then used to predict the missing data point. The curve fit that best predicted the missing value (based on R and Chi-squared) was labeled the “best fit” curve.

RESULTS

Young’s Modulus Curve Fit

Based on the stated criteria Figure 3 shows the “best fit” Young’s modulus curve along with the equation for the curve. This curve produced an R-squared value of 0.999999954.

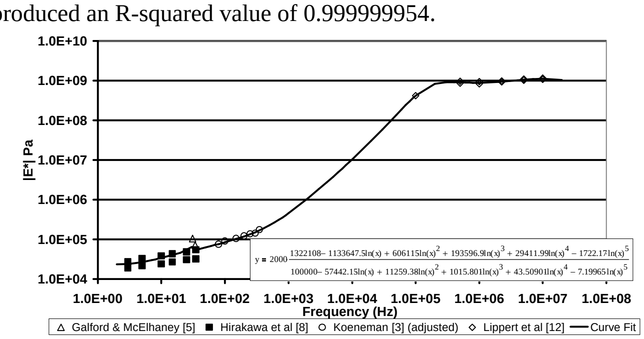

Figure 3: Curve fit produced for Young’s modulus.

Shear Modulus Curve Fit

Based on the stated criteria, Figure 4 showsthe “best fit” shear modulus curve along with the equation for the curve. This curve fit had an R-squared value of 0.999997669.

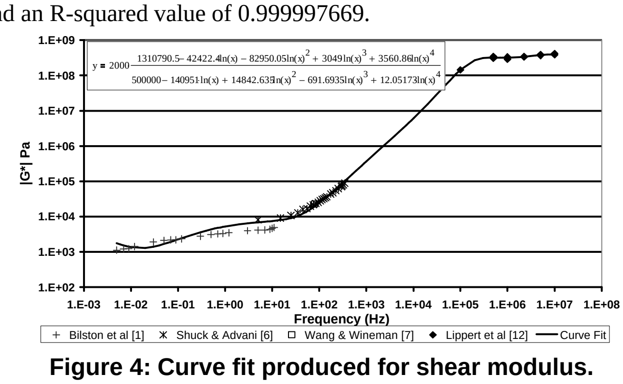

Figure 4: Curve fit produced for shear modulus.

Predicted Properties for the Impact Range

With formulas describing the shape of the property curves, it is possible to predict the properties of brain tissue at frequencies between 1 kHz and 10 kHz, this being the frequency range common for an impact event. Prediction of Young’s modulus and shear modulus is necessary as this range is beyond the limits of current measurement techniques. Table 1 shows the predicted values for this range, based on our curve fit results.

Freq. (kHz)	1	2	3	4	5	6	7	8	9	10
|G*| (kPa)	362	832	1357	1927	2536	3182	3861	4573	5316	6089
|E*| (kPa)	458	1075	1848	2750	3768	4893	6120	7444	8862	10372

Table 1: Table of predicted moduli for impact frequencies.

CONCLUSION

The curves obtained through this work allow a first approximation of brain tissue properties in the range of impact frequencies.

ACKNOWLEDGEMENTS

Funding courtesy CDC-NCIPC grant #CCR-503534-11 and the Ford Motor Company.

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