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Brain Tissue Material Properties: A Comparison Of Results

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ABSTRACT

A series of experimental studies quantifying the material properties of brain tissue have been performed over the past thirty-five years. Most of these studies have utilized oscillatory test techniques to obtain measures of the frequency dependent complex shear modulus for brain tissue. Others have performed compression tests, stress relaxation tests and shear tests to obtain time dependent measures of the material moduli. Because of the variety of test techniques, strain magnitudes and strain rates used in testing it is difficult to compare results from these studies. Furthermore, the rapid development of powerful computing work stations has encouraged a recent interest in finite element analytical models of the head and brain that require accurate brain tissue material properties. These models, usually based on explicit integration finite element analysis codes such as DYNA-3D, generally expect a time dependent stress relaxation form of the shear modulus for a soft viscoelastic solid material. This study converts the results from the studies performed over the past thirty-five years to a time dependent stress relaxation shear modulus form in order to compare them directly.

INTRODUCTION

Over the past thirty-five years a number of researchers have studied the material properties of brain tissue in order to develop a constitutive relationship between stress and strain. A constitutive relation is required for analytically modeling the human brain during potentially injurious events such as head impact in a vehicular crash. Most of these studies utilized oscillatory testing to measure the frequency dependent complex shear modulus of brain tissue although several investigators also performed stress relaxation tests, compression tests or shear tests to obtain a time dependent measure of the tissue stress vs strain properties. Because of the different test techniques used, the different

moduli used to represent the stress vs strain relation, the various levels of maximum strain tested and the fact that only one frequency was tested in many cases, it is difficult to compare results from the different studies. It is also difficult to develop a single continuous stress vs strain relationship for brain tissue over the expected range of loading rates and durations appropriate to potentially injurious head acceleration events.

The development of powerful and inexpensive mini-computer based workstations has resulted in the rapid improvement and proliferation of finite element analysis (FEA) computer codes. This technique has become the preferred method for analytically modeling the head and brain undergoing a large acceleration event such as impact in a vehicular crash. Most of the more powerful dynamic FEA codes are based on the DYNA-3D finite element code. DYNA-3D is an explicit integration code developed at Lawrence Livermore Laboratory which has a linear viscoelastic material model in its library of standardized materials that requires the material parameters for a stress relaxation form of the shear modulus. The stress relaxation shear modulus is a time dependent form based on the application of a step strain resulting in a decaying stress response over time. Few of the published results from the existing studies of brain tissue are presented in the stress relaxation form required by finite element models.

This study reviewed the published data and results from brain tissue material property studies and developed a methodology for presenting the various results on a single time based plot in a stress relaxation form suitable for finite element analytical modeling of the head and brain.

REVIEW OF BRAIN TISSUE MATERIAL PROPERTY STUDIES

A number of studies investigating the material properties of brain tissue utilized oscillatory strain testing to obtain a complex elastic or shear modulus. These frequency dependent results are discussed below and are shown plotted in Figures 1 to 4. Time dependent testing of brain tissue has also been performed using several different experimental techniques such as creep tests, stress relaxation tests and constant strain rate tests. These studies are also discussed below and results are shown on common axes in a stress relaxation form in Figure 5.

Oscillatory Testing

In 1966 Koeneman [in Fallenstein, Hulce and Melvin 1969a, 1969b and in Ommaya 1968] performed creep and oscillatory compression testing of white matter brain tissue obtained from rabbits, rats and pigs. Koeneman performed cyclic compression at frequencies between 80 Hz to 350 Hz and found the complex compression modulus to be in the range of $E^* = 8.8 \text{ kPa}$ to 15 kPa and $E'' = 2.7 \text{ kPa}$ to 9.6 kPa . Assuming that the compression modulus is three times greater than the shear modulus gives an estimate for complex shear modulus of $G^* = 2.7 \text{ kPa}$ to 5.0 kPa and $G'' = 0.9 \text{ kPa}$ to 3.2 kPa . The strain magnitudes tested in the Koeneman study were not reported.

Galford and McElhane [1969] performed compressive creep, relaxation and free vibration tests of rhesus monkey and human brain tissue. The creep and relaxation results are discussed later. The complex compression modulus for human brain tissue is given as $E^* = 66 + i 26.1 \text{ kPa}$ (where the * indicates a complex quantity) at 21 Hz. Dividing by three gives a complex shear modulus of $G^* = 22 + i 8.7 \text{ kPa}$. The tissue tested was 95% white matter and the strain magnitude tested was not reported. Fallenstein, Hulce and Melvin [1969a and 1968b] performed oscillatory parallel plate shear tests of fresh human brain tissue samples at a frequency of 10 Hz. The complex shear modulus ranged from

$G^* = 0.6 + i 0.4$ kPa to $G^* = 1.1 + i 0.6$ kPa. The tissue was white matter and the strain varied from 0.07 to 0.37.

Shuck and Advani [1972] and Shuck, Haynes and Fogle [1970] performed oscillatory shear tests on fresh human brain tissue in a torsional mode at frequencies from 10 to 350 Hz. The resulting complex shear modulus varied from $G^* = 8.0$ kPa + i 3.2 kPa at lower frequencies to $G^* = 30.0$ kPa + i 80.0 kPa at higher frequencies. These researchers felt that the tissue yields and begins to deteriorate at frequencies above 60 Hz. The tissue tested was both gray and white matter and the results were combined. Tissue was tested to a maximum strain of 0.35. Wang and Wineman [1972] analyzed impact probe data collected previously from *in-vivo* tests of rhesus monkey brain tissue performed by Fallenstein, Hulce and Melvin [1969a, 1969b]. A complex shear modulus of $G^* = 2.83 + i 1.62$ kPa was found at 80 Hz. These tests were of necessity performed on the gray tissue of the cerebrum. No strain levels were reported but the nature of the testing would cause the strain to be small.

Arbogast and Margulies [1997] performed oscillatory parallel plate shear tests on porcine brain tissue taken from the brain stem and the cerebrum. Testing was performed at two maximum strain levels of .025 and .05 over a frequency range from 20 Hz to 200 Hz. Results indicated that cerebral tissue was quite different from brain stem tissue at the higher strain level. For brain stem and cerebral tissue the complex modulus at 0.025 strain ranged from $G^* = 1.3 + i 0.5$ kPa at 20 Hz to $G^* = 1.8 + i 2.11$ kPa at 200 Hz. At 0.05 strain, the brain stem modulus was approximately the same as that presented for the lower strain level but the cerebral tissue had a complex shear modulus ranging from $G^* = 0.3 + i 0.3$ kPa at 20 Hz to $G^* = 1.1 + i 1.0$ kPa at 200 Hz. These results convincingly show that different types of brain tissue may have different material response characteristics. The complex shear modulus results from all of these oscillatory studies are plotted in Figures 1 and 2 and again in Figures 3 and 4 at a larger scale. It should be noted that all of these plotted curves are related to the engineering shear strain which is twice the Langrangian shear strain.

Time Dependent Testing

Galford and McElhaney [1969] performed creep tests and stress relaxation tests on human and monkey brain tissue as well as the free vibration tests discussed previously. These stress relaxation tests were done over long periods of time ranging from two to seventy seconds. A typical head impact injury event has a duration of less than a tenth of a second. These results are not representative of the response of brain tissue over the time duration of interest and are only useful as an indication of the long term response of brain tissue. The results from this study are shown in Figure 5 only at a time of two seconds to show how these long duration results compare to the results from other studies. Estes and McElhaney [1970] performed constant rate compression tests on fresh human brain tissue and on Rhesus monkey brain tissue at four rates of 0.05 cm/sec, 0.5 cm/sec, 5 cm/sec and 25 cm/sec. The results from this testing were represented by a material model relating stress to the stretch ratio and the stretch rate. The model chosen by these investigators can not be represented in the form of a stress relaxation function because the model response to a step strain is an infinite stress. The monkey brain tissues was found to be slightly stiffer than the human brain tissue. All of the human brain tissue samples were of white tissue from the corona radiata and all samples were tested to a true strain of 1.0.

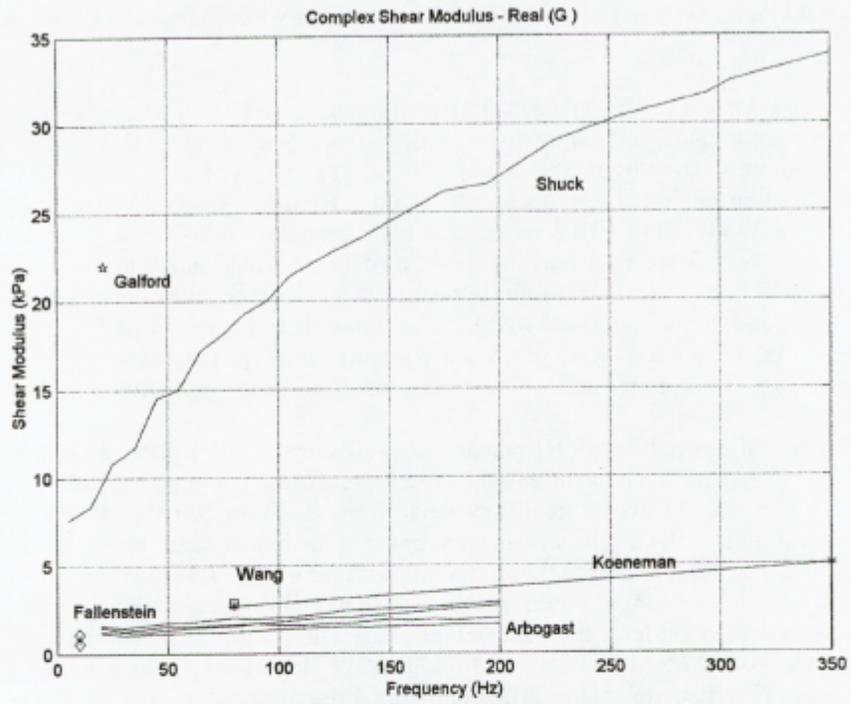


Figure 1. Real parts of the complex shear moduli.

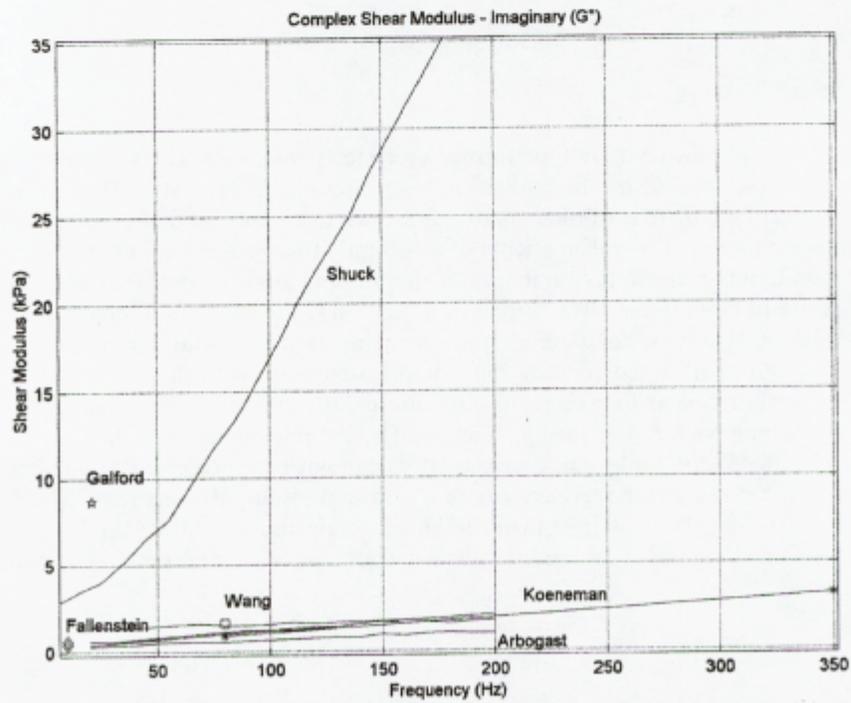


Figure 2. Imaginary parts of the complex shear moduli.

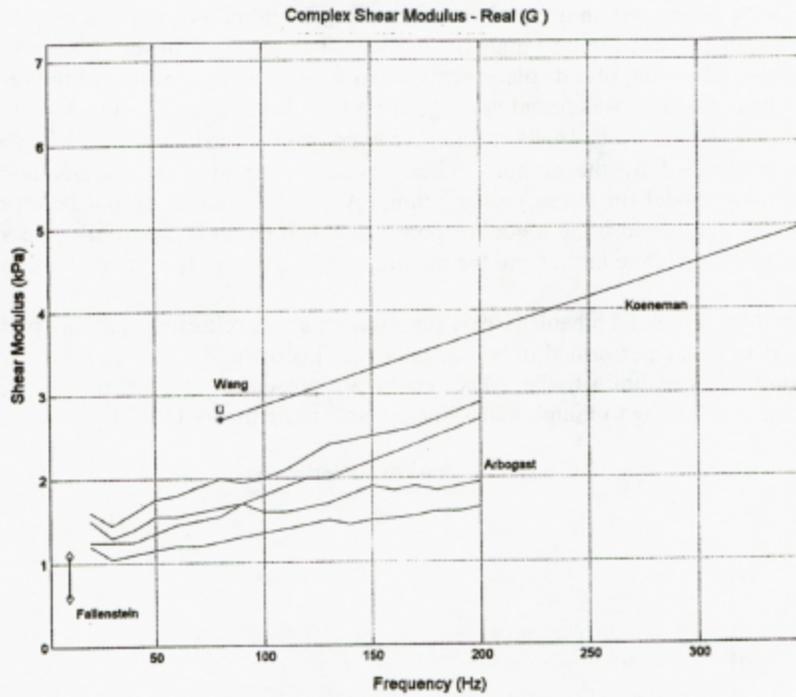


Figure 3. Real parts of the complex moduli at a larger scale

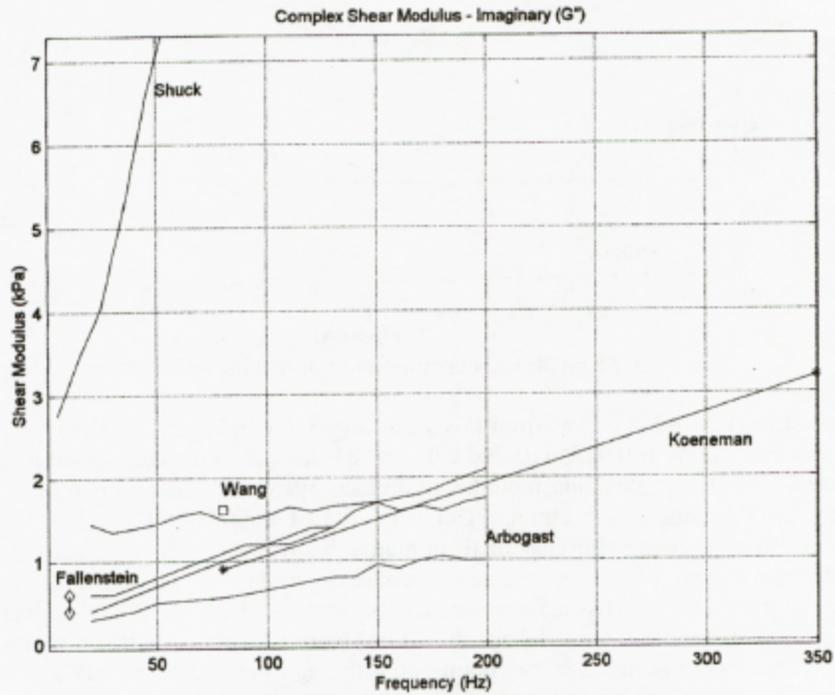


Figure 4. Imaginary parts of the complex shear moduli at a larger scale

Ljung [1975] performed an unusual set of tests in which brain tissue was inserted into a rigid cylinder which was then rotated in an impulsive motion. The response of the tissue was filmed with high speed cameras and the angular displacements fitted to an analytical model of the test setup. The resulting elastic shear modulus was found to range from $G' = 1.3$ to 2.2 kPa and a kinematic viscosity was found to range from $\nu = 1.4$ to 16.4 kPa-sec. An average set of values of $G = 1.7$ kPa and $\nu = 9.0$ kPa-sec was recommended by the author. These values relate to a standard Kelvin-Voigt two-parameter viscoelastic model for stress versus strain. Again, this model cannot be represented as a stress relaxation function because the model response to a step strain is an infinite stress. The tissue tested was mixed gray and white matter and the maximum strain was in the range of 0.8 to 1.0.

Arbogast, Meaney and Thibault [1995] reported on stress relaxation parallel plate shear tests of porcine brain stem tissue performed in two orthogonal directions. Clear differences were found in the directional properties of brain tissue. The results are presented in the form of a reduced shear relaxation function conforming to Fung's quasi-linear viscoelastic theory [1993].

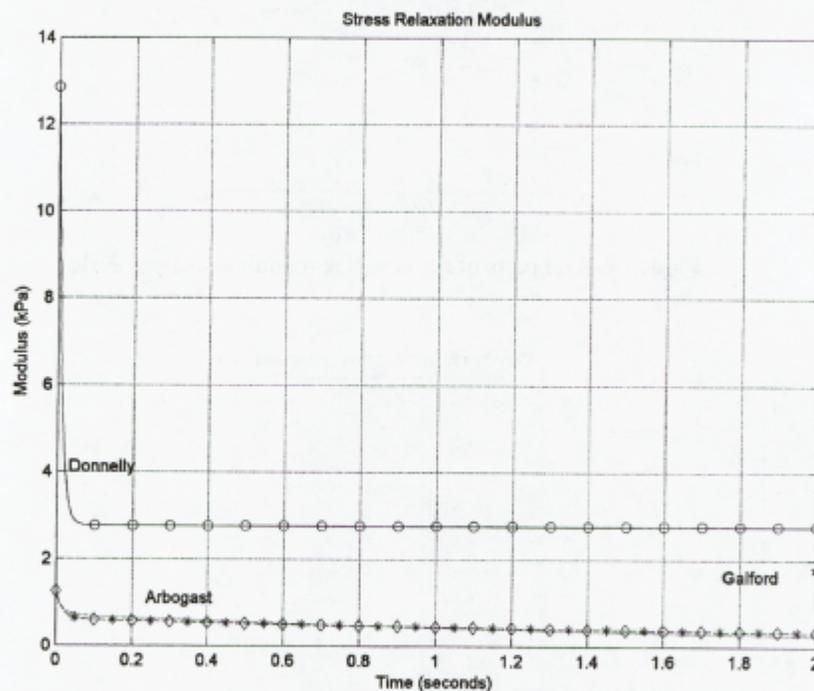


Figure 5. Shear stress relaxation moduli results from several studies

Typical stress relaxation curves from this study are shown in Figure 5. The tissue was tested to maximum tensorial strains of 0.025, 0.05 and 0.075 which are half of the corresponding engineering strains. The resulting stress relaxation modulus is divided by two in order to obtain a shear stress relaxation modulus for engineering strain. Donnelly and Medige [1997] reported on high rate, constant velocity, parallel plate shear tests of fresh human brain tissue. The results from this testing were used to develop a three parameter, nonlinear viscoelastic solid model for human brain tissues that can be used to represent the brain tissue response to a step strain in the form of a stress relaxation test. The stress relaxation curves for this model are shown in Figure 5. The tissue tested in this study was obtained from lateral cored sections of the brain taken through the corona radiata and the cerebral cortex and contained mixed white and gray matter. Maximum strain tested in this study was 0.5 tensorial strain or an engineering strain of 1.0. As discussed above, the value for stress relaxation

modulus from this study was divided by two to obtain a modulus for engineering strain comparable to the moduli shown previously.

OTHER TESTING

Metz, McElhaney and Ommaya [1970] inserted a probe with an inflatable section into living and dead Rhesus monkey brain tissue to measure an elastic compression moduli. The *in-vivo* results ranged from $E = 30$ to 60 kPa and the dead tissue results ranged from $E = 10$ to 50 kPa. Dividing by three to obtain comparable shear moduli gives $G = 10$ to 20 kPa for living tissue and $G = 3$ to 7 kPa for dead tissue. No description of the tissue tested or the strain levels tested was given although probe inflation pressure should correlate with probe inflation volume which, in turn, should be related to strain. The testing of dead tissue was performed immediately after death on the same animal and the decrease in moduli may have been due to the lack of active blood pressure. It is interesting to note that modulus decreased immediately after death and continued to decrease as time passed. Although the elastic shear modulus for dead tissue of $G = 3$ to 7 kPa is similar to results for the real part of the complex shear modulus, as seen in Figures 1 and 3, it is not clear how results from this study relate to results from the other oscillatory and transient studies discussed earlier.

DISCUSSION

The studies of brain tissue material properties can be divided into three groups; (1) oscillatory studies resulting in the complex shear modulus, (2) stress relaxation studies resulting in a shear stress relaxation modulus and (3) those studies with reported results that cannot be examined in comparison to the first two groups without analyzing the original data to develop a basis for comparison. The studies of Estes and McElhaney [1970], Ljung [1975] and Metz, McElhaney and Ommaya [1970] fall into the third group and will not be discussed further. The real part of the complex shear moduli from several studies are shown in Figure 1. It is clear that the results of Galford and McElhaney and of Shuck and Advani are considerably larger than those from all of the other studies. The results from the other studies are all in the same general range of 0.5 to 5 kPa over the range of frequencies from 0 to 350 Hz. Figure 3 shows these results on a larger scale. The four lines representing the recent Arbogast and Margulies data are for porcine brain stem and cerebrum data at two maximum strains and are in general agreement with the results from Fallenstein, et.al., Wang and Wineman, and Koeman.

The imaginary part of the complex shear moduli from the several studies are shown in Figures 2. Once again, the results from Galford and McElhaney and from Shuck and Advani are considerably larger than those from all of the other studies. The results from the other studies are all in the same general range of 0.5 to 3 kPa over a range of frequencies from 0 to 350 Hz. Figure 4 shows these results on a larger scale. The four lines representing the recent Arbogast and Margulies data are again in general agreement with the results from the older studies. The shear stress relaxation moduli are shown in Figure 5 for the Arbogast, et.al. [1995] study of porcine brain stem tissue taken in two orthogonal directions and the Donnelly and Medige model for human brain tissue. The value from the long time duration tests of Galford and McElhaney is also shown at a duration of two seconds. The long time duration constant stress levels from stress relaxation data are a measure of the elastic response of the materials. For these studies the long term moduli values range from 0.5 to 3 kPa and are similar in magnitude to the real parts of the complex shear moduli shown in Figure 1 and 3.

In order to compare the results from the first two groups of brain tissue studies (Figures 1 to 5) the complex shear moduli and/or the stress relaxation moduli must be transformed to a common

moduli. Because current finite element modeling technique prefers a stress relaxation moduli form, the complex shear moduli will be transformed to the stress relaxation moduli form. The mathematical tool for transforming the frequency based complex shear moduli to a time based stress relaxation modulus is the inverse Fourier transform [Tschoegl 1989]. The equation for conversion from frequency space to time space for the complex shear modulus is

$$G(t) = \text{Fourier}^{-1} \left[\frac{G^*(\omega)}{i\omega} \right]$$

which can be obtained by taking the inverse Fourier transform of the heredity integral of the harmonic form of the viscoelastic stress versus strain equation. Several assumptions are made when transforming the complex shear modulus data to a time based stress relaxation form using the inverse Fourier transform. The complex modulus data has been truncated to eliminate the negative frequency data which must be recreated and has an absolute value equal to the mirror image of the positive frequency data. The time based stress relaxation moduli must be real; therefore, the frequency based complex moduli will be conjugate anti-symmetric, i.e., the real part of the complex moduli will be an even function of frequency and the imaginary part will be an odd function of frequency. The transformed data set is negatively offset by a constant equal to the magnitude of the first point, i.e., the DC offset. The discrete inverse Fourier transform of the complex shear modulus must be scaled by the Nyquist frequency to approximate the continuous relaxation modulus.

The complex shear modulus data from the brain tissue studies shown in Figures 1 and 2 have been transformed and are shown in Figure 6, and again in Figure 7 at a larger scale, along with the shear stress relaxation data previously shown in Figure 5. In order to obtain a frequency based series for transformation purposes, the complex shear modulus data from the Fallenstein, et.al, Wang and Wineman, and Koeneman studies have been combined into a single data set and a least squares straight line has been fit to the data set. This combined data is denoted as the "Combined" shear stress relaxation curve in Figure 6 and 7. The Galford and McElhaney data has not been included in this exercise because it was only collected a very long time durations.

The shear stress relaxation curve derived from the Shuck and Advani data is considerably larger than the shear stress relaxation curve reported and derived from the other studies. The Donnelly and Medige relaxation curve is several times smaller than the Shuck and Advani curve but is still twice the magnitude of the stress relaxation curves from the remaining studies. The derived stress relaxation curve for the combined data of Fallenstein, et.al, Wang and Wineman and Koeneman agrees very well with the stress relaxation results of Arbogast and Margulies and with the transformed results of Arbogast et.al. These curves are better examined in Figure 7 at a larger scale. The stress relaxation curves from Arbogast and Margulies and Arbogast et.al. are in excellent agreement and were taken at the same laboratory and may be the same data.

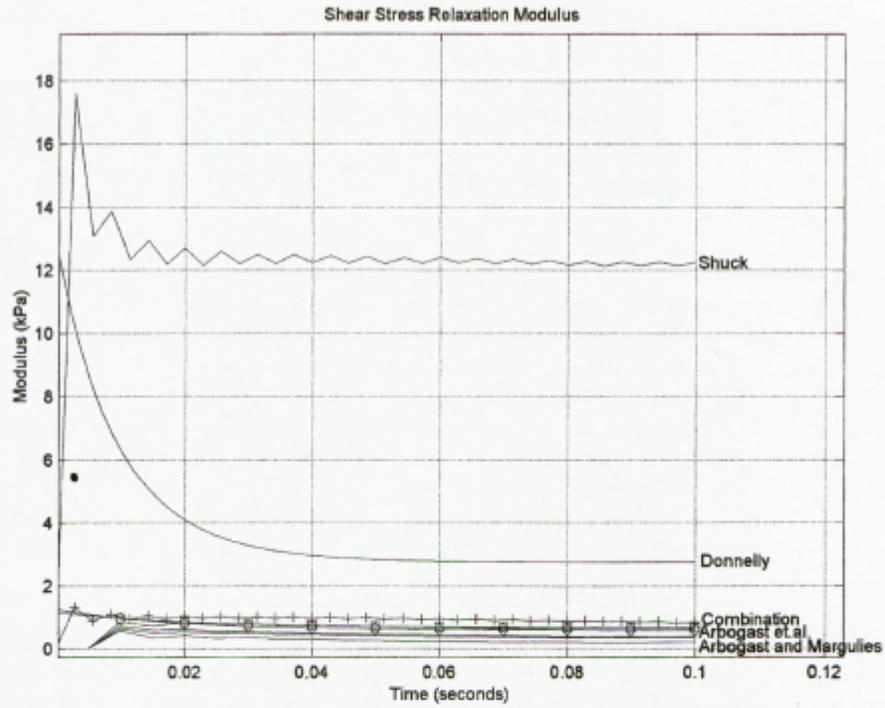


Figure 6. Comparison of shear relaxation moduli

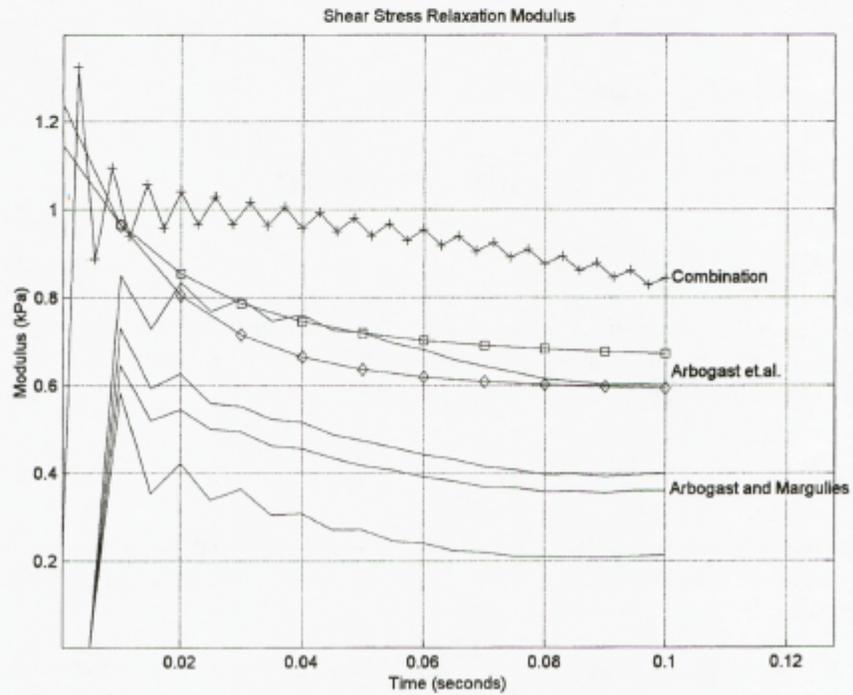


Figure 7. Comparison of shear stress relaxation moduli at a larger scale

CONCLUSION

The complex moduli results from the various oscillatory studies for the material properties of brain tissue can be transformed to more useful shear stress relaxation moduli using the inverse Fourier transform. The stress relaxation form is preferred by most finite element analysis codes. This transformation allows the results from most of the reported studies of brain tissue material properties to be compared to each other.

The complex moduli results from the Shuck and Advani study and the Galford and McElhaney study are considerably larger in magnitude than the results from the other oscillatory studies. It is not clear why this is the case; however, the Shuck and Advani study utilized oscillatory torsional shear testing and most of the other oscillatory studies (Fallenstein, et.al., Arbogast and Margulies, Wang and Wineman, and Koeneman) utilized translational shear testing. The results from the time based studies (Arbogast, et.al. and Donnelly and Medige) were approximately in agreement and also agreed with the transformed results from the oscillatory studies with the exception of the Shuck and Advani results. The stress relaxation results reported by Galford and McElhaney were taken at long time durations of two seconds and longer. Although these data are not appropriate for studying injury producing events, the magnitude of the stress relaxation modulus is similar to the long time duration moduli from the other studies.

The resulting shear stress relaxation curves from the various brain tissue material property studies shown in Figures 6 and 7, excepting the Shuck and Advani results, are sufficiently in agreement that a composite function shear stress relaxation function could be developed for use in finite element head models. This composite function would serve to provide a standardized viscoelastic brain tissue behavior for near term FEM modeling that will allow the analytical results from the various analytical models to be compared. In the longer term, more brain tissue property research needs to be performed since even small differences in material response may have significant effects on analytical results [Arbogast and Margulies 1997].

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