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Dynamical properties of the brain tissue under oscillatory shear stresses at large strain range

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Abstract. In this experimental work, we study the viscoelastic behaviour of in vitro brain tissue, particularly the white matter, under oscillatory shear strain. The selective vulnerability of this tissue is the anisotropic mechanical properties of theirs different regions lead to a sensitivity to the angular shear rate and magnitude of strain. For this aim, shear storage modulus (G′) and loss modulus (G″) were measured over a range of frequencies (1 to 100 Hz), for different levels of strain (1 %, to 50 %). The mechanical responses of the brain matter samples showed a viscoelastic behaviour that depend on the correlated strain level and frequency range and old age sample. The samples have been showed evolution behaviour by increasing then decreasing the strain level. Also, the stiffness anisotropy of brain matter was showed between regions and species.

1. Introduction

To obtain insight into brain injury mechanisms, the internal mechanical response of the head under impact conditions has to be known. Obviously, it is not possible to study in experiments the influence of a violent shock on an *in vivo* human head, to reach the tolerance criteria of the head. We found in the literature that most studies on the mechanical behaviour of brain matter are digital simulations using finite elements FE; the other experimental studies often use either *in vitro* brain samples of material under dynamic conditions [1] or *in vivo* samples using image analysis techniques [2]. Most of the *in vitro* tests described in the literature were based on creep and relaxation in compression and shear tests, or on dynamic frequency or strain sweep experiments. To characterize viscoelastic brain behavior under small strain, most of the *in vitro* experiments have been performed dynamically, commonly using a dynamic frequency sweep. Thus, most of the dynamic frequency sweep protocols have investigated tissues in the linear strain domain. Although most of the dynamic frequency sweep tests have been carried out in shear, some dynamic frequency sweep experiments have been done in tensile/compression mode.

In 2008, Hrapko et al. published a literature review focusing on *in vitro* experimental protocols [1]. As well as Cheng et al. published literature reviews on comparing brain and spinal cord mechanicals properties [3]. In 2010, Di Iewa et al. presented a review using imaging applications for the mechanical characterization of brain tissue [4]. Also in 2010, Chatelin et al. complements these existing literature reviews on brain tissue mechanics [5] by presenting more recent results and by focusing on the comparison between *in vitro* and *in vivo* tests, greatly developed since 2005, especially those concerning Magnetic Resonance Elastography (MRE). Brain tissue consists of gray and white matters. Mechanically, the matters are relatively incompressible, nonlinear and viscoelastic, as concluded by [6-8]. The gray matter is typically considered to be isotropic and the mechanical response of white matter may depend on orientation [9]. Both quasi-static and dynamic brain matter analysis was dealt with in this study as they provide complementary information with more recent results [5]. In this light, we interest to study in this paper the dynamical response of brain tissue with time under the large strain range. As well as we tried to complete our contribution in understanding of the brain tissue mechanical properties in transient state [10], by the study of their properties under oscillatory strain solicitations. Dynamic strain and frequency sweep tests were used to test different old age samples in shear deformation.

2. Materials and Methods

In our study, we have used the dynamic shear test to determine the mechanical response of animal brain samples (lamb and bovine brain tissue) at large strain. These experiments were realized on samples harvested and preserved few hours to three days to study the degradation brain matter with time.

2.1. Samples Preparations

These experiments for this study were performed *in vitro* on lamb and cow brain aged between 6 and 12 months. Lamb brains were used because of their availability. The brains (one of bovine and four of lambs) were collected a few minutes to one day after the animals were killed at a local slaughterhouse. The brain tissue was preserved in physiological solution at 6°C, in icebox, to preserve the ionic balance during transport. The experiments reported in this paper were completed within 72h postmortem. Annulus sample of diameter 25 mm and thickness 0.8 to 3 mm were delicately excised from sections of gray matter (thalamus) and white matter (corona radiate and corpus callosum). Cylindrical plugs of the white matter (thickness = 4 mm) were then harvested manually from the corpus callosum and corona radiate using a punch (diameter =25 mm) and a surgical knife. The specimens were then bathed in the solution until testing. The experiments were performed at temperature (20±0.01°C).

2.2. Dynamics tests

Rheological tests were carried out on the brain samples at swelling equilibrium (25mm diameter disk, 2 mm thick) using a stress-controlled MCR302 rheometer (Physica Company, Germany) in parallel-plate geometry. The samples were tested in a dynamic regime at small and large amplitudes of deformation (0.1% to 50%). During the measurements, samples were kept in hydrated chamber at controlled temperature (20°C). The linear viscoelastic region was determined by strain sweep measurements which allowed us to set adequate stresses so that the resulting strains did not damage the brain sample just for confirmed our tests with literature. Then, the non-linear viscoelastic behaviour was study by dynamic frequency sweep under large strains. Dynamic controlled strains tests and dynamic frequency sweep tests were performed with frequencies ranging from 1 to 100 or 600 (rad/s) to determine the variation of storage and loss modulus (G′) and (G″), respectively), under various shear strains levels. To study the sample degeneracy the same tests were performed on samples preserved for one day, two days and three days.

3. Results and Discussions

The main objective of this work was to study the mechanical response of brain matter, obtained from different species (lambs and cow) and preserved from few hours to few days, to the large shear strains.

3.1. Species differences

To compare the response of the two different brains animals, dynamics frequency sweep measurement results obtained from same region of brain samples of two different species tested at *5%* strain level are shown in Figure 1 and 2. Numerous studies have demonstrated the non-linear viscoelastic behavior of adult brain tissue over a wide range of strains and strain rates [7], [11-15]. To predict tolerance criteria for non-linear, large deformation inertial brain injury, we were interesting to characterize the brain tissue properties at strains larger than 1%.

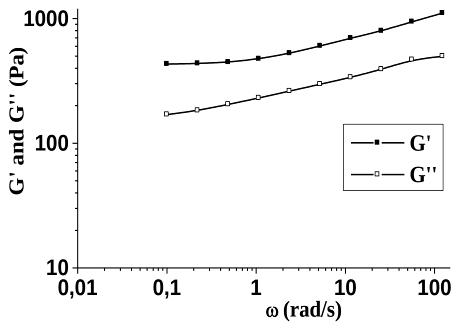

Figure 1. Storage modulus (G′) and loss modulus (G″) obtained in dynamic frequency sweep with 5 % of strain for corona radiate (CR) of the lamb brain tissue

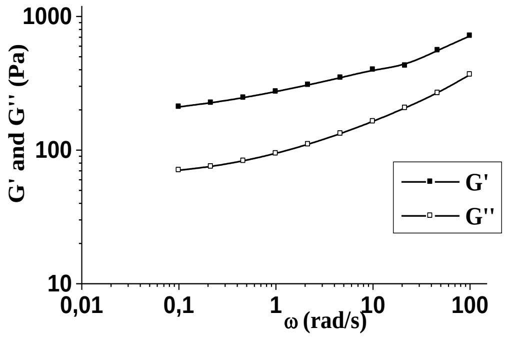

Figure 2. Storage modulus (G′) and loss modulus (G″) obtained in dynamic frequency sweep with a 5% of strain for corona radiate (CR) of bovine brain tissue

The storage (G′) and loss modulus (G″) varied with testing frequency indicating a viscoelastic response, (G′) is higher than (G″), with same evolution of the tow components as in literature results [1], [4], [11], but with differences in values level of each sample source.

3.2. Control strain

Measurements of controlled strain tests at different fixed frequencies were presented in Figure 3. From these experiments, the results showed that the storage modulus (G′) of the brain tissue started to decrease for an applied strain value about 1% of strain at low frequency.

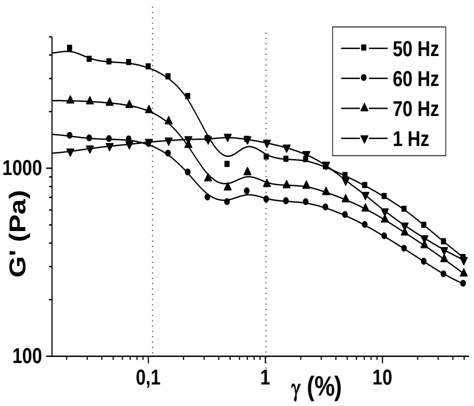

Figure 3. Mean amplitudes sweep response of (G′) of TH and CR samples at four different frequency values

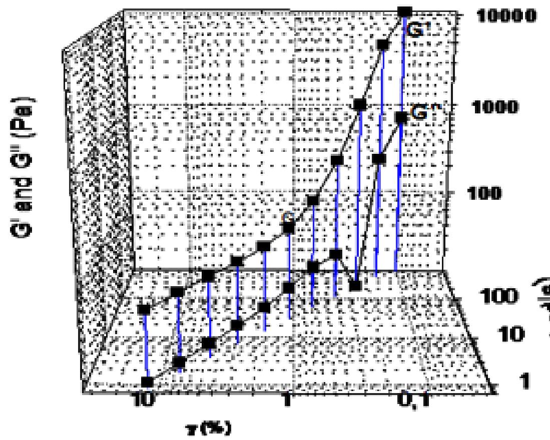

Figure 4. Storage modulus (G′) and loss modulus (G″) obtained in dynamic frequency sweep with a strain 5% of corona radiate (CR) from bovine brain tissue

Compared with similar work done on porcine cerebral tissue realized by Nicolle et al [16], the same limit was obtained. However, this linear viscoelastic limit decrease to 0.1% of strain for high frequency.

From another controlled strain test, with frequency sweep, results (figure 4) showed that:

- the storage modulus (G′) found to be larger than loss modulus (G″) (viscoelastic behaviour);
- storage modulus G′ and loss modulus G″ showed significantly frequency dependence;
- for high frequency we can't use large strain (bulck flow).

To study the strain level effect on the viscoelastic parameters (G′) and (G″), we have fixed the strain level in each test then we have varied the frequency.
The results of three large strain levels of CR from one day old bovine brain tissue were presented in Figure 5. In Figure 6, the results of CR from one day old lamb brain tissue were presented.

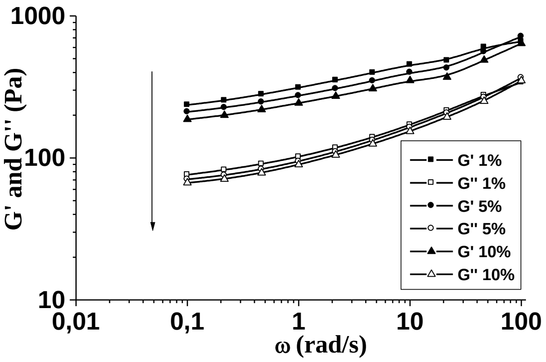

Figure 5. Mean frequencies sweep response of storage modulus, G' and loss modulus, G″ at three levels strain of CR from one day old bovine brain tissue

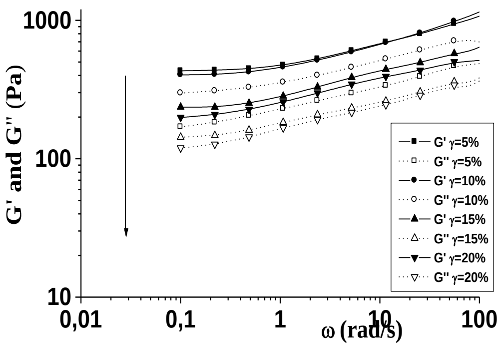

Figure 6. Mean frequencies sweep response of storage modulus, G' and loss modulus, G″ at four levels strain of CR from fresh lamb brain tissue

From these results, we can show that at large strain, storage modulus G′ and loss modulus G″ increase with increasing frequency, contrast they decrease with strain level. As well as, the difference between G′ and G″ become smaller with frequency.

To study the degradation effect, we have increased the strain level gradually in each sweep frequency test applied on Corpus callosum sample reserved for one day, and then we have decreased it for the second time as same. The results of storage modulus (G′) evolution are show in Figure 7.

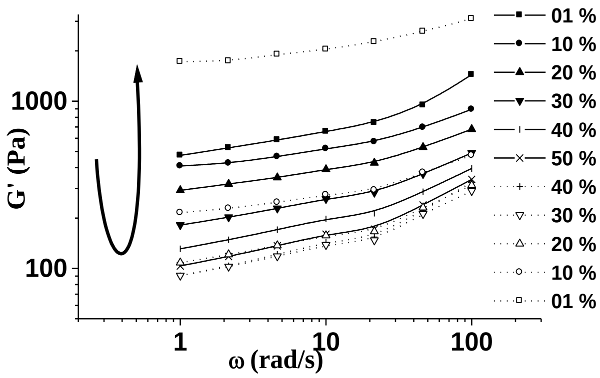

Figure 7. Series of frequency response of storage modulus, (G′), for the increasing then decreasing strain levels imposed at the same sample (CC) of one day old lamb brain

3.3. Syntheses results

The results of our study are compared with the published literature regarding animal and human brain tissue properties. A review of the mechanical properties of adult human and animal brain was realized by Chatelin et al. [7].

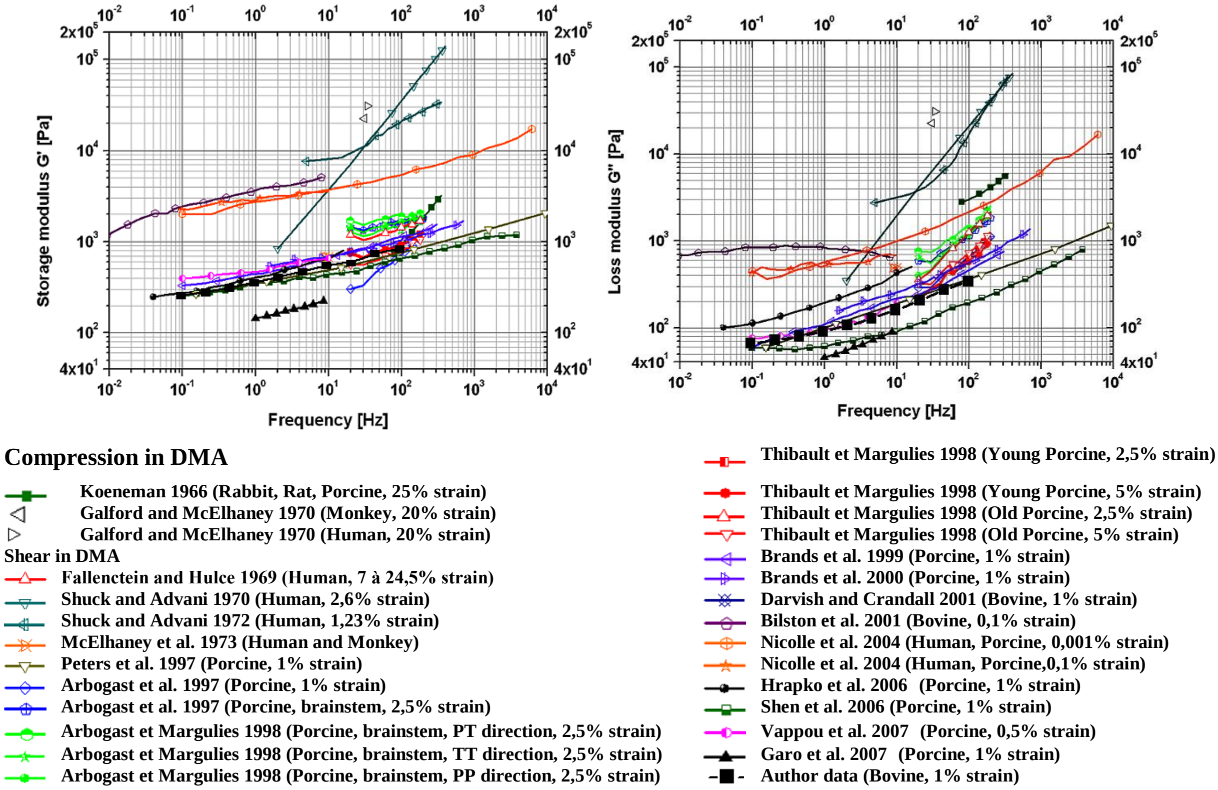

Figure 8. Comparison of (G′) and (G″) of in-vitro brain tissue reported in the literature in dynamic frequency sweep shear tests. In colour from the ref [2] with in black line and square symbol of author results (bovine, 1% of strain). In all studies the storage modulus is observed to increase with increasing frequency.

This review demonstrated that the reported properties of brain tissue from different species and testing conditions varied by as much as an order of magnitude summarize the storage modulus G′ (Figure 8) and loss modulus G″. However, in all results G′ and G″ increased with increasing frequency. Compared it with our results, taken a low strain range of 1%, we can show that these storage and loss modulus were superposed with Peters et al. results in which they tested porcine brain tissue under the same strain level.

4. Conclusion

This experimental study present oscillatory characteristic of *in vitro* animal brain tissue using large shear strain range. The measurements were carried out on samples taken from different brain species and different regions preserved from few hour to few days. The data demonstrated that the dynamical properties of brain tissue depend to various experimental conditions. It also proved that the viscoelastic parameters: storage modulus G′ and loss modulus G″ increase with increasing frequency which is confirmed with literature. These parameters decrease with strain level and time (fresh or not brain sample). From frequency sweep tests by varying the strain level applied on the same sample, we found that the brain tissue is not reproductive with increasing then decreasing strain level which indicate the degradation of sample.

5. References

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