STUDIES OF THE MOTION OF THE BRAIN AT A SUDDENLY APPLIED ROTATION OF THE SKULL.

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INTRODUCTION

Most investigators of brain injury mechanisms agree that rotational motion of the skull is the major agent in producing hemorrhages and lesions at the superficial parts of the brain (See e.g. Ommaya and Hirsch, 1971). It must then be essential to know the character and magnitude of the resulting distortion of the brain. Determination of this distortion requires knowledge of the rheological parameters controlling the internal motions in the brain. For this purpose a two-parameter model has been developed, enabling comparatively simple experimental investigations and an exact solution of the equations of motion.

DESCRIPTION OF THE MODEL

The model consists of an infinitely long, rigid cylindrical shell, filled with a Voigt material. At purely rotational motion no dilatation occurs so that the two material parameters will be the kinematic viscosity and the shear modulus. The choice of a cylindrical geometry is made in order to facilitate an analytical solution of the motion. Furthermore, the solutions obtained from this geometry, are considered to reflect rather well what happens in the vicinity of the sagittal plane. It also enables an experimental set-up which is not too complicated. A Voigt material was chosen because it is the simplest two-parameter material exhibiting the property of returning to its original, undeformed state after unloading.

The solution of the differential equations arising from the mathematical formulation of the model has been previously accomplished (Ljung 1972). To make simulations of internal motions of the brain possible, the two material parameters appearing in this solution have to be determined experimentally.

THE EXPERIMENTAL PROCEDURE

The experimental determination of the material parameters is performed on brain matter from human corpses. No attention has so far been paid to the difference between living and dead tissue. The brain matter is inserted into a cylinder of radius 30 mm, which can be subjected to a sudden rotation by means of a pneumatic piston. See figure 1.

When the piston is activated, its stroke is transferred to the cylinder by means of a steel wire. The resulting rotational acceleration of course depends on the piston response to the applied air pressure. This response is shown in figure 2. The effective stroke length can be varied by changing the length of the wire. The pulse duration and amplitude can thus be chosen within apparent limitations.

The brain matter is marked with pins inserted along a diameter on one of the two surfaces in order to facilitate analysis of the motion. The course of events is recorded by means of a high speed camera. Normal speed settings will rate from 3 000 to 5 000 pictures per second.

MEASUREMENTS RESULTING FROM EXPERIMENTS

The high speed film pictures obtained in experiments show the deformation state of the brain at typically 200 time values. Cf figure 3 where T = 4 msecs. The interval between two consecutive pictures is generally not constant, but only on rare occasions does this change in film speed have any effect during the relatively short picture sequences studied. The position of each pin to be analyzed is then measured by means of a projecting microscope with digital read-out.

One difference between the experimental set-up and the mathematical model is that in the experiments the cylinder is of finite length, terminated at free surfaces, whereas in the mathematical model a plane problem is analyzed i.e. no axial displacements are allowed. The validity of applicating the plane deformation hypothesis on the experiments can be checked by calculating the radial displacements of each pin as a function of time. Since, for a free surface, an axial displacement interacts with a radial displacement much more directly than with the tangential displacement, a check of the influence on the tangential displacements from the inevitable axial displacements can be made by comparing the magnitude of the radial displacements (which should be zero in the ideal case) with the magnitude of the tangential displacements. Excepting some experimental failures, the maximal radial displacement has been less than 4% of the maximal tangential displacement. Obviously then, for the purposes of this analysis, the motion of the free surface of the brain matter can be regarded to be nearly the same as for the plane case.

NUMERICAL ANALYSIS OF EXPERIMENTAL DATA

The next task is to choose the kinematic viscosity and the shear modulus so as to make an optimal fit of the mathematical model to the experimental data. This is done numerically using the least squares method. A loss function is formed by squaring the difference between measured data and simulated data acquired from the mathematical model, and then summing over all data points. This loss function, which is a function of kinematic viscosity and shear modulus only, is minimized using the Fletcher-Powell algorithm. (See Fletcher and Powell, 1963).

DISCUSSION OF THE RESULTS

At this stage, only one experiment has been completely analyzed. The results of the measurements are shown in figs. 4-8 together with simulations obtained from the mathematical model. The values for the kinematic viscosity and shear modulus were chosen optimally according to the method described earlier. The kinematic viscosity was found to be 0.27 m^2/sec, whereas the shear modulus was 1900N/m^2. It should be underlined, however, that these results have been obtained from one experiment, only.

From fig. 4 the maximal peripheral velocity can be found to be approximately 4 m/sec. This velocity is not very high compared to what could be expected when a car occupant hits the windscreen at a frontal collision. Measurements of the maximal shear, averaged over the outer 10% of the radius, give a value of about 45 degrees. Thus the brain movements which could be expected in head impact situations are indeed substantial. Obviously the danger of injury in the corresponding regions of a human brain in situ will be high. This matter will be more thoroughly discussed in a forth-coming paper.

A comparison of measured and simulated data in figs. 5-8 give at hand a rather good agreement, expecially during the first part of the motion, where stresses and strains are highest. As calculated from the loss function value, the deviation between measured and simulated displacements, averaged over time and radius, is 0.6 mm.

More experiments (covering as wide a range in acceleration amplitude and duration as possible) of course have to be performed to test the capability of the model to reflect the physical reality. If the material model can thus be proven satisfactory, more complex geometrical configurations should be analyzed. The idea would of course be to fit the form of the brain case better, in order to study the brain motion even at other positions than the neighbourhood of the superior sagittal sinus, where already the present model should be fairly satisfactory.

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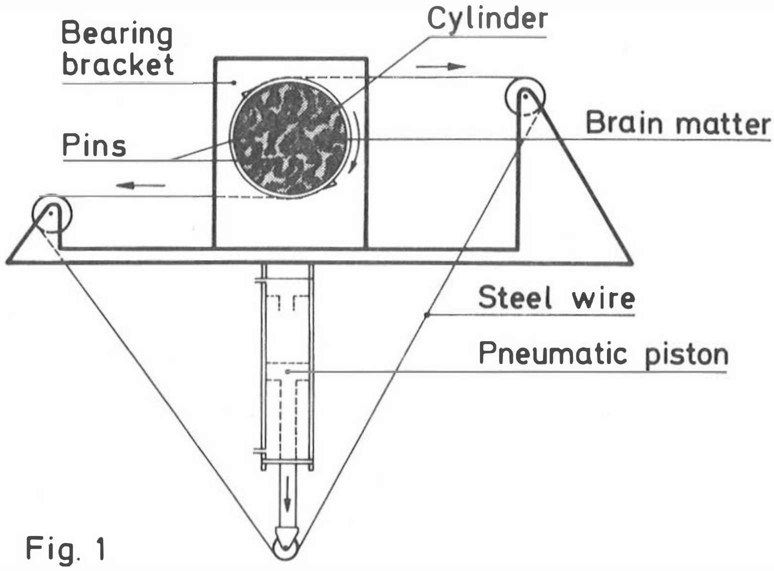
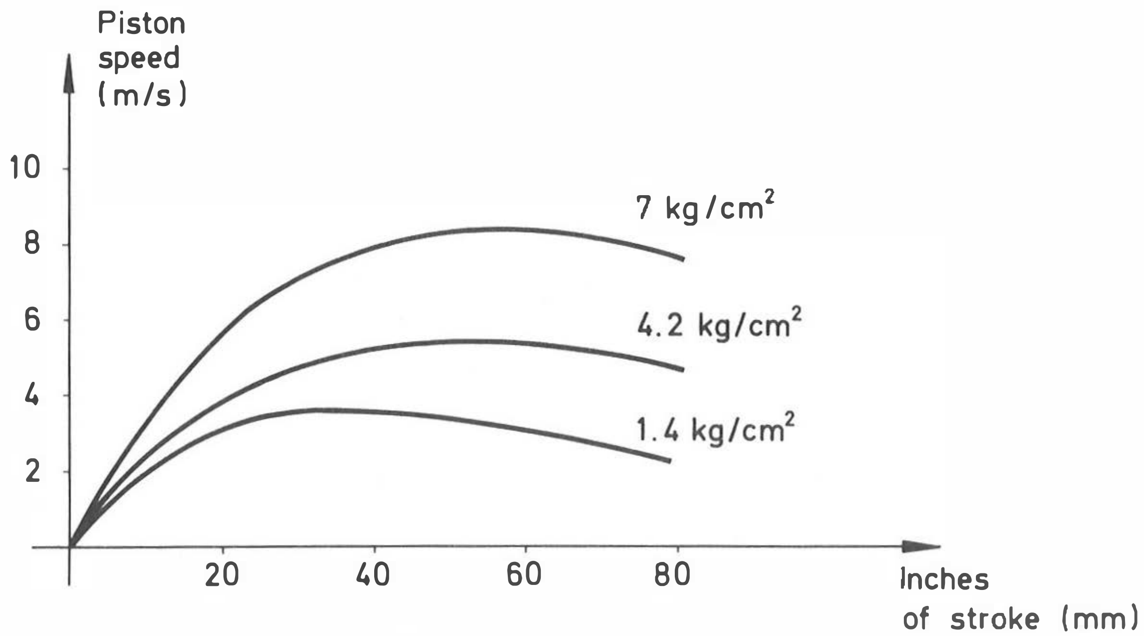


Bearing bracket
Cylinder
Pins
Brain matter
Steel wire
Pneumatic piston

Fig. 1



Piston speed (m/s)
10
8
6
4
2
20
40
60
80
7 kg/cm²
4.2 kg/cm²
1.4 kg/cm²
Inches of stroke (mm)

Fig. 2

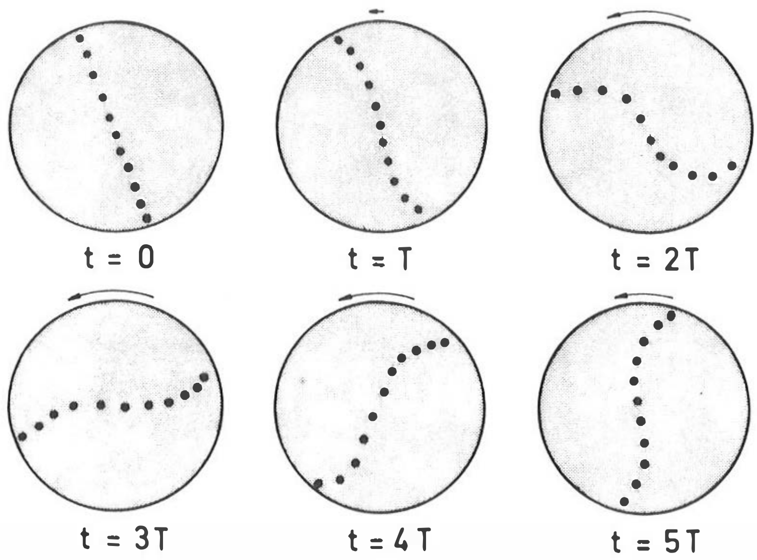


Fig. 3

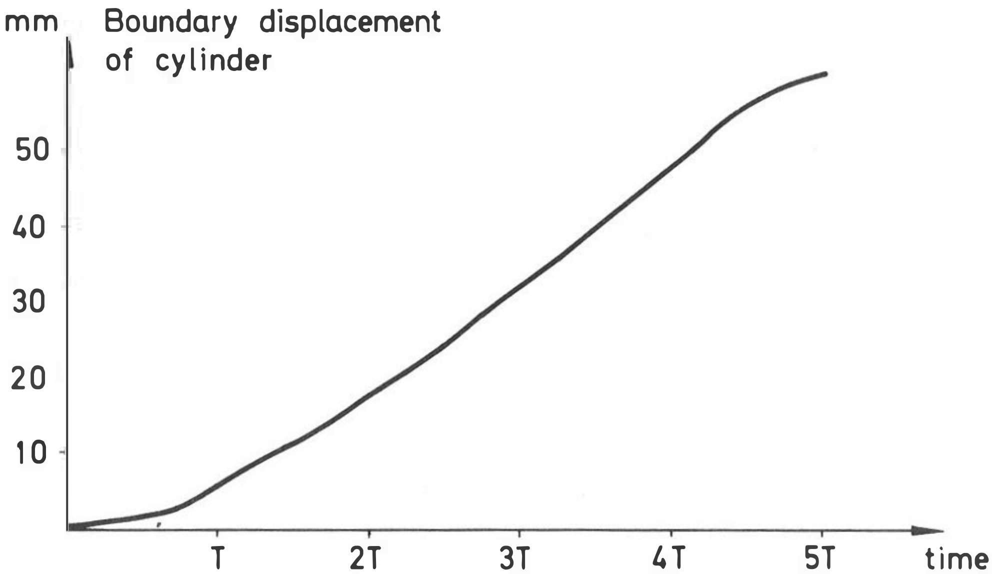


Fig. 4 T = 3.5 msec

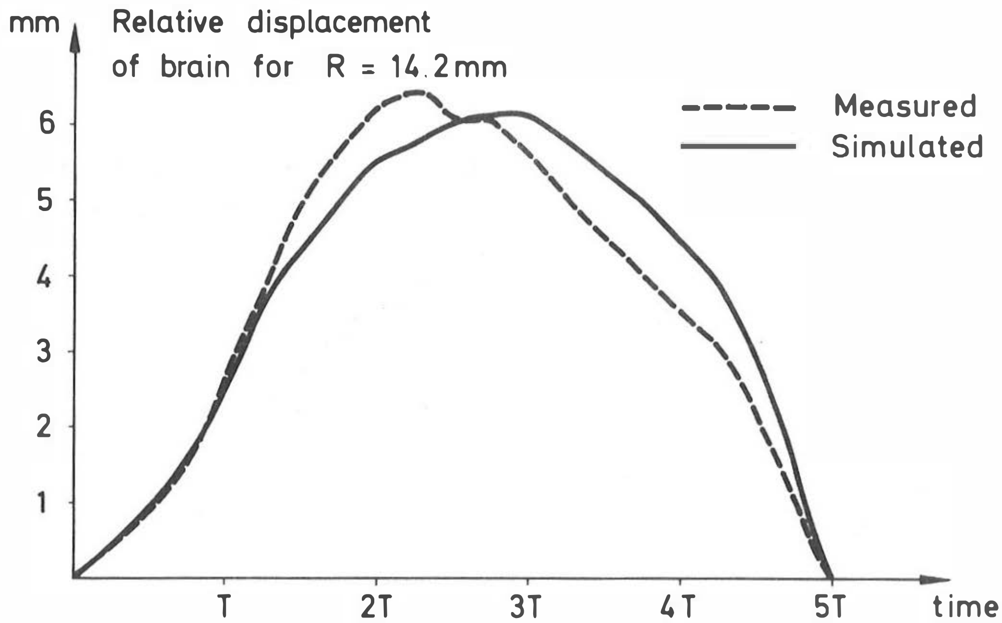


Fig. 5 T = 3.5 msec

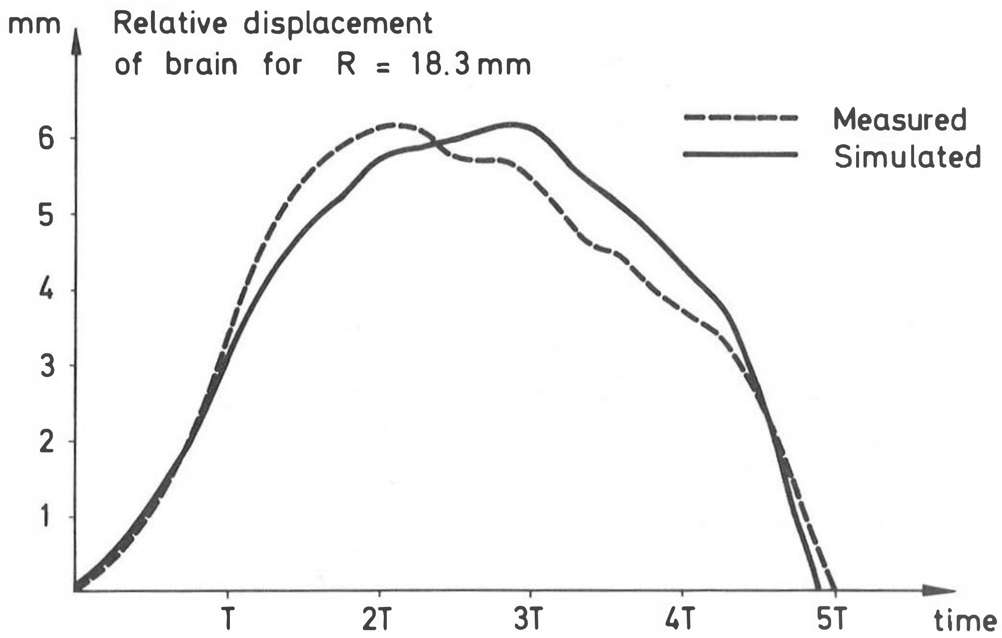


Fig. 6 T = 3.5 msec

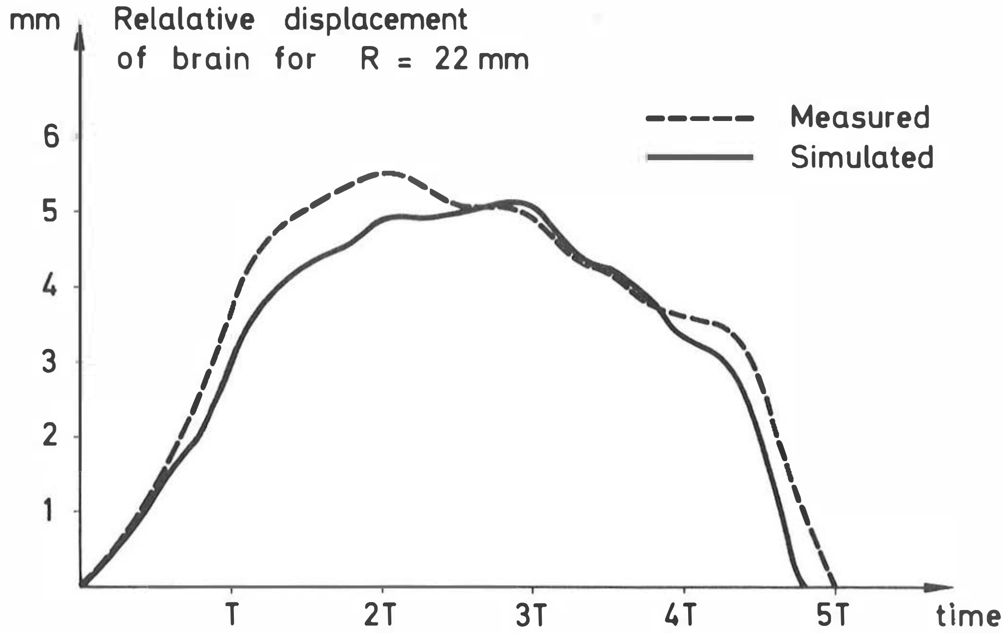


Fig. 7 T = 3.5 msec

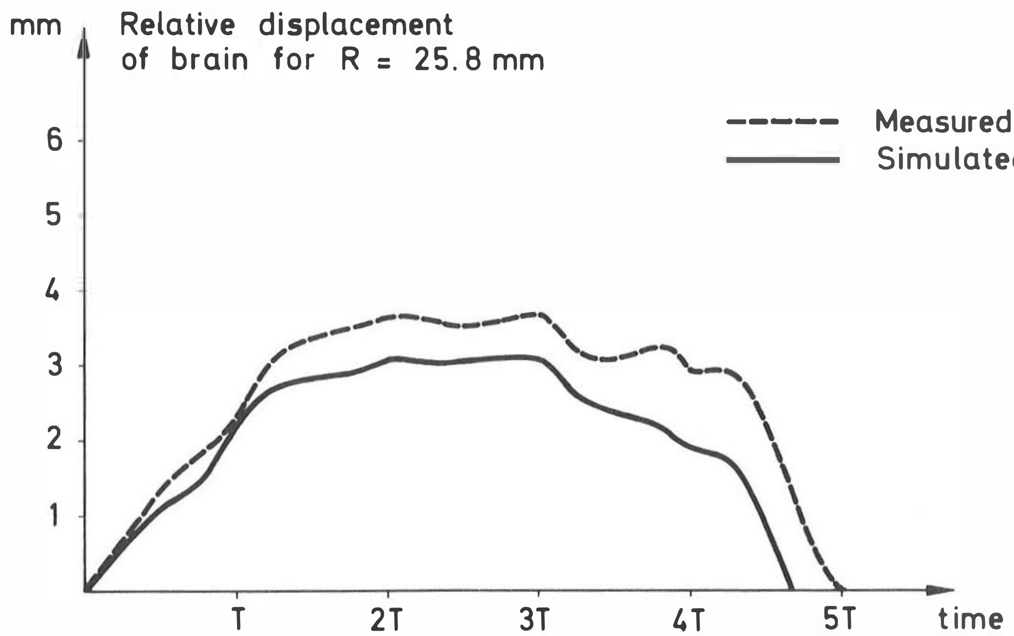


Fig. 8 T = 3.5 msec