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Dynamic Properties of the Parasagittal Bridging Veins

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Summary. A method for investigating stretching of small blood vessels is presented. Stress and strain properties of the isolated parasagittal bridging veins were studied. These veins were stressed along their long axis and torn apart at various constant strainrates. The bridging vein's strain capacity was found to be dependent on strain rate, maximal strain was markedly reduced as the rate was increased. The maximal tension in the veins increases as the time to tearing decreases. The tearing tension was shown to be lower for bridging veins as compared to larger veins (femoral, popliteal, inferior vena cava).

Zusammenfassung. Eine Methode zur Untersuchung der Reißfestigkeit bei Streckung kleiner Blutgefäße wird beschrieben. Die Spannungs- und Dehnungseigenschaften isolierter parasagittaler Brückenvenen (Vv. cerebri sup.) wurden untersucht. Die Venen wurden in ihrer Längsrichtung belastet und rissen bei verschiedenen konstanten Dehnungsgeschwindigkeiten. Das maximale Dehnungsvermögen wurde bei größerer Dehnungsgeschwindigkeit stark herabgesetzt. Die maximale Spannung in den Brückenvenen stieg, wenn die Zeit bis zum Abriß kürzer war. Die Zerreißspannung war für Brückenvenen geringer als für größere Venen (V. femoralis, V. poplitea, V. cava inf.).

Key words: Traumatology, disruption of bridging veins — Bridging veins, disruption.

The superior cerebral veins together with the surrounding connective tissue (Pacchionian granulations) and the sometimes accompanying arteries comprise the only connections between the brain's mantel edge and the rigid dura. It is well known that these bridging veins can rupture as a result of trauma to the head. It is assumed that as a result of angular acceleration of the head the bridging veins can rupture into the subdural space (Fig. 1), intraarachnoidally or subcortically, which would thus cause subdural, subarachnoidal or intracerebral bleeding, respectively. These injuries are not uncommon, for example, in boxers or car occupants who during a head-on collision strike their head against the windshield or the steering wheel. In order to formulate protective measures against such an injury — especially with respect to the construction of automobiles — one must have knowledge of the conditions under which the injuries in question can arise. It is therefore important to know, among other things, the mechanical properties of the bridging veins.

In the present study the stress strain relationship at different strain rates was studied by causing the veins to tear after a unidirectional pull.

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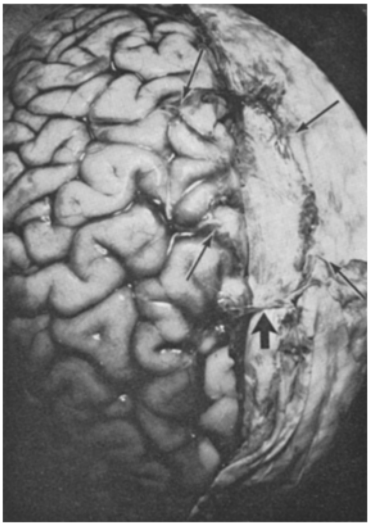

Fig. 1. Disruption of bridging veins in the subdural space (thin arrows). Notice the connection to the dura before the vessel empties into the superior sagittal sinus. At the heavy arrow an intact bridging vein is seen

Material and Methods

Bridging veins were secured from autopsy specimens. Veins from the lateral convexity of the brain were chosen preferentially. These veins are free from large amounts of surrounding connective tissue. Blood vessels were preserved up to 6 hrs in 0.9% saline solution at room temperature until the tests were conducted. The specimens were tested within 48 hrs after death. Specimens were taken from 11 persons (7 men, 4 women) who had no previous brain injury. The subjects' ages varied between 13 and 87 years. The tested veins were macroscopically intact. Analysis of 22 strain tests was carried out, with the following assumptions:

1. The tissue is assumed to be homogeneous.
2. The wall of the bridging vein is assumed to be of uniform thickness.
3. The tissue is assumed to be incompressible.

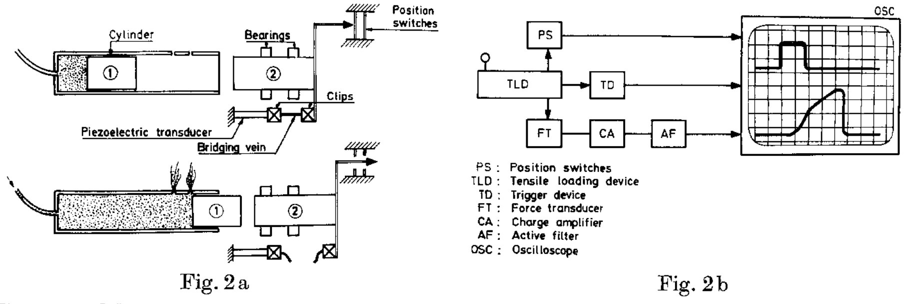

Fig. 2a

Fig. 2b

Fig. 2a and b. Experimental setup. a Appearance before and after the trial. b Diagramatic sketch of the apparatus

The experimental set-up is shown in Fig. 2. The bridging veins were loaded to the point of rupture in a strain test device. This consisted of two movable massive steel cylinders (see Fig. 2). In a tube which was open at one end the first cylinder (*1*) could be manaeuvered with compressed air. By varying the pressure one could select the cylinder's acceleration and final speed. The other movable cylinder (*2*) was guided on a plane bearing. The cylinders had the same diameter and were mounted so that their long axes in the direction of movement coincided. A clip for the insertion of the veins and an arm for marking position were mounted on cylinder (*2*). On a separate table was fastened a piezo-electric force transducer (Kistler type 9203). The force transducer was connected to an oscilloscope through a charge amplifier and an active filter. Between cylinder (*2*) and the force transducer was inserted the trial vein which was stretched until a signal from the force transducer was obtained. The length of the bridging veins between the clips was measured. This length was designated the initial length. Cylinder (*1*) was then accelerated in the tube. After passing a number of evacuation ports in the tube the cylinder was not appreciably affected by the driving pressure. At a constant speed cylinder (*1*) transferred therefore its kinetic energy to cylinder (*2*) through a central impact. The impact started the oscilloscope sweep by means of a contact switch. Those forces which after the impact now acted on cylinder (*2*) (for example frictional forces in the bearings and the force which in time is built up in the bridging vein) reduced the velocity of the cylinder. It was shown, however, that the loss of velocity during one trial was less than 4%, and the speed was therefore considered constant. The mean velocity was measured with two position markers. Perpendicularly to the direction of motion of cylinder (*2*) were mounted two pencil leads at a welldefined distance from each other. During forward motion the arm of cylinder (*2*) broke the pencil leads which were incorporated as breakers in an electric circuit. Thus, the time between the breaks was recorded from the oscilloscope and the mean velocity could be calculated.

In spite of the fact that the force transducer was mounted on a separate table strong vibrations were recieved from the impact of the two cylinders. To eliminate these vibrations of which the lowest frequency was of the order of 10000 Hz, the signal was filtered. To this purpose a fourth-order Butterworth filter was built which cut off sharply at 5000 Hz (Fig. 3).

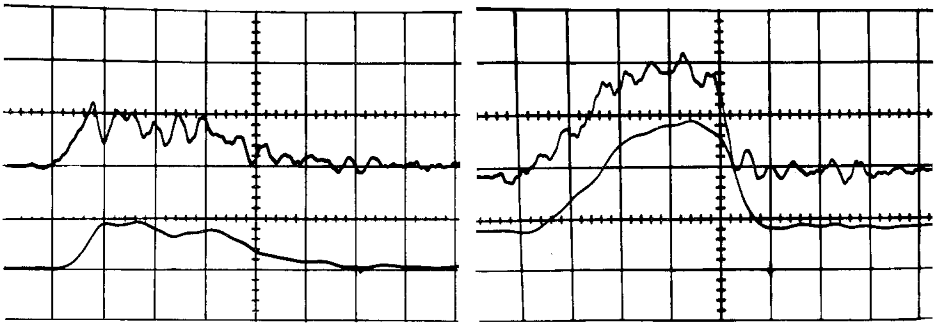

Fig. 3. The effect of the active filter during disruption of the bridging veins. The upper curve shows the original signal, the lower curve shows the same signal after filtering

During the trials the rupture of the bridging veins occurred at random positions. This result supports the second assumption on uniform wall thickness along the vessel and that the phenomenon of weave propagation can be neglected (see below). However, in about one fourth of the conducted trials the bridging veins were torn at their insertion in the clip. These trials were considered void and disregarded since they were assumed to result from the pinching effect at the clips. In order to determine the cross-sectional area of the bridging veins transverse sections were prepared of the vessel wall. Before the vein was straintested a small piece of the vessel was cut off, placed in Tissuetek and frozen. This embedding medium undergoes a small volume change with freezing and therefore the deformation of the vessel was minimal. The specimen of bridging vein was thereafter sectioned perpendicularly to its long axis and the section was transferred to a glass slide and photographed.

The oscilloscope sweeps were photographed with a Polaroid camera.

Calculations

The raw data consisted of oscilloscope pictures with the force in the bridging vein recorded as a function of time. Fig. 4 shows two typical results. The force reaches a peak or a plateau and returns gradually to base line. A probable interpretation of these data is that rupture of a bridging vein occurs gradually. The tissue probably begins to disrupt when a plateau or the peak of the force curve is reached, and the length of the bridging vein at this point is therefore designated the stretched length when disruption begins. Since the cylinder velocity has been calculated: $v = s/tp$ where s is the distance between the pencil leads and tp the time between the breaks, the elongation of the bridging vein can be calculated as $ls = l \times ts$, where ts is the rise-time of the force. The strain is now calculated as $\varepsilon = ls/lr$ where lr is the vein's initial length. The strain rate is defined as $\dot{\varepsilon} = v/lr$, which gives comparable results for tested veins of different lengths. To provide comparable results for the force development in the bridging veins the stress is calculated $\sigma = F/A$ where F is maximal force and A is the cross-sectional area of the wall of the tested bridging vein. The cross-sectional area of the bridging veins was determined by the following method: The picture of the cross-section of the

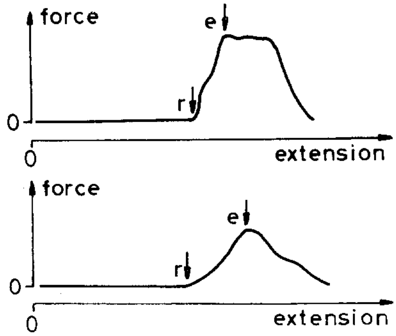

Fig. 4. Two typical results. r relaxed length, e extended length

bridging vein was copied on photographic paper. A micrometer scale was photographed at the same enlargement and copied on the same type of paper. If the micrometer scale is l_m and its picture is l_{mb} the degree of enlargement of the length scale becomes $l_{mb}/l_m = k$. If the veins cross-sectional area is assumed to be A_{bv}, the area of the picture also becomes $A_{bbv} = k^2 \times A_{bv}$. The surface of the photographic paper used is measured A_p and the paper is weighed m_p. The picture of the vein's cross-section is cut out along the outer and inner contoures, whereafter the cut-out is weighed m_{bbv}. Now the paper's weight per surface area is indicated:

$$c = \frac{m_p}{A_p} = \frac{m_{bbv}}{A_{bbv}} = \frac{m_{bbv}}{k^2 A_{bv}} = \frac{m_{bbv}}{\left(\frac{l_{mb}}{l_m}\right)^2 A_{bv}}$$

whereby the cross sectional area of the bridging veins is derived as

$$A_{bv} = A_p \frac{m_{bbv}}{\left(\frac{l_{mb}}{l_m}\right)^2 m_p} = \text{konst}\, m_{bbv}.$$

Results

The results are reported in Fig. 5. Fig. 5a shows the ultimate strain of the veins in percent as a function of the strain rate. Fig. 5b shows maximal stress in the bridging vein as a function of the time to the beginning of disruption.

Discussion

Rupture of the superior cerebral veins can occur in the subdural space, intraarachnoidally and subcortically. The cause of these subdural and intraarachnoidal ruptures is considered to be a concequence of the brain gliding with respect to the dura when the head is exposed to blunt trauma, whereby these veins and surrounding connective tissue are stretched. When the head is exposed to angular acceleration deformation of the brain substance arises, especially in the subcortical

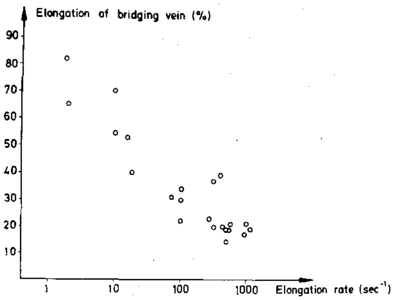

Fig. 5a

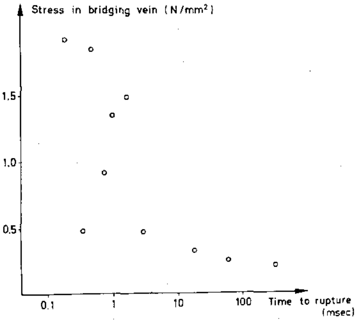

Fig. 5b

Fig. 5a and b. Experimental results. a Ultimate strain vs. strain rate in a bridging vein. b Maximal stress vs. time to beginning of disruption in a bridging vein tissue levels. The resultant displacing tensions may therefore be the cause of subcortical ruptures. Mochizuki has shown that human veins (popliteal, femoral and inferior vena cava) have a strain capacity of about 100% when they are loaded statically. The literature contains no information on the veins' properties with transient dynamic loading. If, however, such a strain capacity could be assumed to apply to the bridging veins there would have to be considerable movement or deformation of the brain before the veins would rupture. From Fig. 5a it is seen that, indeed, the strain capacity for bridging veins is large at low strain rates, but that the ultimate strain is strongly diminished as the rate increases.

The assumption that the bridging veins are homogeneous implies that the spread in the results can arise due to individual differences among test specimens, for example, differences in construction and age-dependent variations. From Mochizuki's work it is seen, for example, that the stress tension at rupture and the strain capacity for veins (popliteal, femoral and inferior vena cava) are, respectively, 10 and 18% lower for the age group 60—69 years compared with the group 20—29. The study of the differences in strain capacity related to strain rate conducted among various age groups would mean a very large experimental sample. The purpose of this investigation is, however, to study the average properties. As the age dependent changes are small compared with the dynamic changes, the amount of test material can be limited without thereby disturbing the tendency of the results.

Fig. 5b shows the stress in a bridging vein as a function of the time to rupture. For short loading times the vessels can tolerate higher stress. This is a common finding in investigations of other types of material. Von Gierke has shown that the tolerance to traumatic influences of varying degree and duration is dependent upon the mechanical resonance of the respective tissue. If the duration of the trauma is long compared to the natural period of the system (bridging vein) the tolerance becomes dependent upon the size of the force. If, on the other hand, the duration is short in relation to the natural period the tolerance becomes dependent not only on the size of the force but also on the duration, that is, the force's time-integral or the impulse (see Fig. 6).

By shortening the loading times wave propagation in the vessel can influence the result. Since the bridging veins are inserted between a movable and a fixed

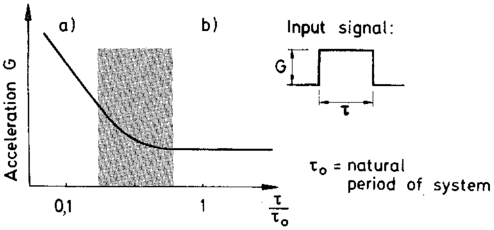

Fig. 6

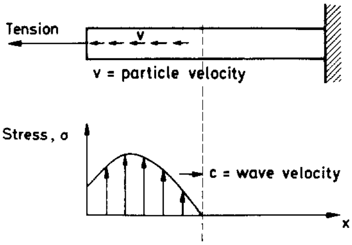

Fig. 7

Fig. 6. Theoretic impact tolerance curve of one-degree-of-freedom-system. The curve shows the pulse height (as a function of the ratio pulse length to the natural period of the system) nessecary to achieve equal dynamic response. τ_0 natural period of the system, τ pulse duration

Fig. 7. Schematic representation of a tensile pulse

point it could be surmised that the portion of the bridging vein which is closest the movable point of insertion would be stretched and torn before the portion closest the fixed point of insertion had time to be affected in any appreciable degree (see Fig. 7). That would mean that the calculated strains were too low. In order to disregard the effects of wave propagation the wave would have to have enough time to be reflected 10 times before the trial was over. Information is lacking on the speed of sound in bridging veins. If, however, the speed of sound is assumed to be $c = 1000\,\mathrm{m/sec}$ (c for the brain $= 1500\,\mathrm{m/sec}$) a sound wave would be reflected more than 10 times in a one cm-long bridging vein specimen as soon as the loading time surpassed 0.1 msec. The effects of wave propagation can therefore be neglected, a supposition supported also by the above-mentioned observation of vein rupture at random points. The effect of wave propagation would have caused tearing of the vein close to the movable insertion.

The maximal stress for bridging veins is low compared with that for larger veins (popliteal, femoral and inferior vena cava). The trials reported here were conducted on vessels from cadavers and it would be relevant to question whether the material properties are not quickly altered after death. However, there are reasons to assume that such is not the case since according to Koishi the mechanical stability for blood vessels is about 4 days.

Based on the reported results it is natural to choose stretching as the injury-producing variable. The movements and deformations to which the brain is exposed under the influence of external blunt trauma is determined by the trauma's direction, intensity and duration. The counter-forces which are caused by tension in the bridging veins produce probably only a very slight change in the kinetic energy of the brain. The bridging veins can therefore be assumed to follow the brains movements passively and rupture when the dynamic tolerance is exceeded. Since the strain-strain-rate ratio for bridging veins is known the tolerance can be given in the form of permissable accelerations of the head as soon as the brain's deformation under the influence of external trauma is known. These deformations can attain centimeter size with impacts against the head which are comparable to those which arise during an auto collision.

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