Increased Intracranial Pressure and Tentorial Shear Strain

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Summary

Tentorial herniation is caused by a pressure gradient between supra- and infratentorial compartments and the herniated brain is burdened with a force, which is called shear strain at the edge of the tentorium. The purpose of the present study is to clarify the relationships between increased intracranial pressure, the pressure gradient and the tentorial shear strain. Twenty-three monkeys were used and intracranial pressure was raised by inflation of an epidural balloon placed in the right temporal region. The supratentorial pressure was found to be always higher than the infratentorial pressure and the pressure gradient became greater as intracranial pressure increased. The shear strain at the tentorial edge began to develop as soon as the balloon was expanded, and showed a slow and steady increase even when the intracranial pressure was only slightly increased and the pressure gradient did not have any effect. The degree of the tentorial edge descent observed by X-ray was, however, variable depending upon the animals used. The tentorial edge ceased to descend at the moment the tentorial shear strain was 80-140 mm Hg. At this point and thereafter, the characteristics of both herniated brain and tentorial edge changed from elastic to plastic, and the damage caused by the strained tentorial edge is thought to be tremendously extensive. Our dynamical study of transtentorial herniation shows clearly that the magnitude of shear strain was greater as a local forced pressure than supra- and infratentorial pressure.

Key words: Intracranial pressure, pressure gradient, tentorial shear strain, descent of tentorial edge, transtentorial herniation, viscoelastance

Introduction

The living brain is a kind of viscoelastic substance with a compressible compartment. Increased intracranial pressure in cases with supratentorial mass lesions develops a pressure gradient between supratentorial and infratentorial compartments, which brings about transtentorial herniation. The herniation causes distortion, compression and displacement of the architectural arrangement in the brain tissue. The herniated brain through the tentorial hiatus develops a shear strain at the edge of the tentorium. It is the shear strain rather than the pressure that is of prime importance in physiopathological changes of the displaced brain.

The purpose of the present investigation was to study the dynamical relationship between intracranial pressure and the transtentorial herniation in the course of increased intracranial pressure, and to correlate the tentorial shear strain with the pressure gradient. Particular attention has been given to the living dynamics of tentorial herniation.

Material and Methods

Twenty-three monkeys weighing 4.1–8.7 kg were used in the experiment. The animals were anesthetized with intravenous sodium pentobarbital (Nembutal®), 20–25 mg/kg. Tracheotomy and intubation were performed. The animals were fixed in the prone position in a
modified stereotaxic frame to enable roentgen examination. Body temperature was maintained by heating lamps. All the procedures were performed under spontaneous respiration. Arterial blood gas was checked by a gas analyzer (ABL 1 Radiometer Copenhagen). Right tempor-occipital craniotomy was performed. A small balloon was placed epidurally in the temporal region to increase intracranial pressure. A small sensor was fixed to the tentorial edge in order to measure the shear strain and a tiny lead piece was attached next to the sensor for monitoring the descent of the tentorial edge on radiograms. This procedure was performed under an operative microscope (Fig. 1). Lateral ventricular fluid pressure (VFP) and cisterna magna pressure (CMP) were also measured using a semiconductor film strain transducer (SFT). Supratentorial epidural pressure was measured by means of a SFT attached directly to the dural surface through a burr hole in the left parietal region. Infratentorial epidural pressure was measured by a SFT placed through a burr hole in the suboccipital region. Cranial defects were closed with cyanoacrylate and methyl-cyanacrylate.

Fig. 1 Upper The right temporo-occipital lobe is retracted and the edge of the tentorium is exposed. The short arrow indicates the edge of the tentorium. Double arrows indicate a sensor. The long arrow indicates a lead piece. Lower Small sensor for measurement of the tentorial shear strain.

Fig. 2 The linearity of a sensor was checked before use. Double arrows indicate a load transducer. Single arrow indicates a sensor.

Fig. 3 Calibration of the tentorial shear strain at the end of experiment. Single arrow indicates a sensor. Double arrows indicate a tip of load transducer with soft rubber.
metaacrylate. The balloon was continuously inflated at the rate of 1.1-4.4 ml/hr with radiocontrast material using a pump. The sensor (KFC-C11 strain gauge Kyowa Dengyo Co., Ltd., Tokyo) for measurement of tentorial shear strain was bonded on the surface of a stainless steel foil, 50 μ in thickness (Fig. 1). The linearity of the shear strain sensor was checked by means of a load transducer (20T-10B Kyowa Dengyo Co., Ltd., Tokyo). As a standard, a load transducer was used and the correlation was plotted on an X-Y recorder (3078 Yokogawa Electric Industrial Co., Ltd., Tokyo) (Fig. 2). The supratentorial brain was gently removed at the end of each experiment and calibration of the sensor was made with the sensor left intact at the edge of the tentorium (Fig. 3). The tip of the load transducer was gently applied to the sensing area of the sensor. The output voltage of the sensor was plotted on the X axis, and that of the load transducer on the Y axis, and the correlation was drawn on an X-Y recorder (Fig. 3). The tentorial shear strain was calibrated by a comparison method. The sensing area of the sensor was measured with the use of the universal tool microscopic measuring equipment (Type TMU Tokyo Kōgaku Co., Ltd., Tokyo). Arterial blood pressure was measured by a polyethylene catheter inserted into the abdominal aorta via the left femoral artery. Respiration was monitored by a thermister. Systemic blood pressure, intracranial pressure, respiration and shear strain were continuously recorded on a polygraph (RM-85 Nihon Kohden Kogyo Co., Ltd., Tokyo).

Results

Intracranial pressure

Intracranial pressure was measured in the right lateral ventricle and cisterna magna in 10 of the 23 animals. VFP and CMP, particularly the latter, however, did not correctly represent
intracranial pressure at extreme levels due to blockage at the tip of the cannulae or cerebrospinal fluid leakage. In a later series of this investigation, intracranial pressure was measured as epidural intracranial pressure (EDP) by means of the SFT transducer. The correlation between EDP and VFP was satisfactory, and each value did not fall far from the line of identity as intracranial pressure was raised (Fig. 4).

The correlation between supratentorial and infratentorial pressures
The correlation curves between mean supratentorial and infratentorial EDP was always higher than the identity line during expansion of supratentorial epidural balloon (Fig. 5). The pressure gradient was found to be larger as supratentorial EDP was progressively increased.

Tentorial shear strain and pressure gradient
Tentorial shear strain was measured in gm/sq mm. This gm/sq mm unit was converted into mm and Hg. The correlation between tentorial shear strain and pressure gradient is shown in Fig. 6. The correlation between the shear strain and pressure gradient was quite variable. Tentorial shear strain was already found even when the pressure gradient was still small. The shear strain showed a slow but steady increase from the start of balloon expansion. The intracranial pressure was only slightly increased in the initial stage of balloon inflation, and the pressure gradient could not be taken into account. The tentorial shear strain, however, increased significantly even in the initial stage of increased intracranial pressure. It was further noted that while the pressure gradient across the tentorium increased up to 10 mmHg, tentorial shear strain progressively increased. The time factor in inflation of the balloon was not of importance in the development of shear strain (Fig. 6).

Descent of the tentorial edge and supratentorial EDP
At frequent intervals during the expansion of the balloon, descent of the tentorial edge was observed by radiography. The degree of descent of the tentorial edge was quite variable depending upon the animals used. The edge of tentorium descended more rapidly in the initial stage than in the later stage of increasing intracranial pressure (Fig. 7) and it continued to descend until the supratentorial pressure reached about 50 to 70 mmHg.
Descent of the tentorial edge and shear strain

The correlation between the descent of the tentorial edge and shear strain is illustrated in Fig. 8. The edge of the tentorium descended with the pressure gradient until the tentorial shear strain reached approximately 80–140 mmHg. Shear strain continued to increase even after descent of the tentorial edge had ceased.

The shear strain and supra- and infratentorial pressures

The corresponding values of the infratentorial pressure and shear strain were compared with increasing supratentorial pressure (Fig. 9). EDP has been reported to be higher than VFP. On the other hand, there is a report to the contrary that they do not significantly differ from each other. In our experimental study, EDP was almost equivalent to VFP. The fluid pressure should be measured with caution, because of possible obstruction at the tip of the catheter and cerebrospinal fluid leak around the catheter. We believe that the measurement of EDP is a reliable and safe method not only in experimental animals but also in clinical practice.

The physio-pathological effects of increased intracranial pressure should be discussed from the standpoint of hydrostatic pressure and stress-strain, that is, a kind of force applied to a viscoelastic substance. The term “pressure” should be used in hydrostatic system only. Intracranial pressure as a whole, however, can be treated simply as “pressure” where it is relatively low and where Pascal’s law can be applied. The intracranial pressure is equally increased in all portions of the cerebrospinal fluid space by infusion of fluid into the subarachnoid space when the intracranial cerebrospinal pathways are intact. When the pressure is equally transmitted throughout the
Cerebrospinal fluid is not compressible although the living brain tissue contains compressible compartments. The brain is a viscoelastic substance whose characteristics change from elastic to plastic according to pressure levels.5,6,12,13)

On the other hand, expanding mass lesion in the supratentorial space gives rise to a pressure gradient between supra- and infratentorial compartments and may cause brain distortion, compression and displacement. Physio-pathological changes accompanied by distortion, compression and displacement of the architectural arrangement in the brain tissue are of importance as focal signs in clinical practice, even if a rise in intracranial pressure is not found, because they will possibly induce shear strain which eventually may cause dysfunction of the nervous system. A viscoelastic substance resists deformation when stress is applied and returns to its original shape and position when the stress is removed. Cairns' stated that the brain contains elastic materials that resist distortion and displacement, and tolerates differences in pressure within the brain itself. The existence of a pressure gradient across the tentorial incisura in cases of raised supratentorial pressure has been reported.9,16) An intercompartmental pressure gradient may occur between the cerebral hemispheres, between supra- and infratentorial and spinal compartments.4)

The present investigation showed pressure gradients developing between supra- and infratentorial compartments when intracranial pressure is progressively increased because of a supratentorial focal expanding mass. The pressure gradient in the initial stage of intracranial pressure seems to depend on obliteration of the pathway of cerebrospinal fluid. When the subarachnoid space surrounding the tentorial incisura is completely blocked by further increase of intracranial pressure and the descent of the tentorial edge ceases, the pressure gradient increases—even more progressively. The development of intercompartmental pressure gradient may be somewhat related to the location, direction and duration of the expanding mass.17) This pressure gradient is accompanied by transtentorial herniation.4) The herniation is a displacement of the brain tissue. The force of the herniation is not that of

Fig. 9 Upper Correspondence between shear strain and supratentorial pressure. Lower Correspondence between infratentorial and supratentorial pressure.

cerebrospinal fluid pathways, a pressure gradient does not exist between any compartment of the intracranial space and the brain is neither displaced nor distorted by the increase of pressure.
hydrostatic pressure, but that of stress-strain. The change of architectural arrangement of the brain tissue is significant rather as shear strain than local tissue pressure. During a later period of expansion of the supratentorial balloon, the herniated hippocampal gyrus forces its way into the space between the distorted brain stem and the strained edge of the tentorium and shear strain increased progressively. The present dynamical study shows clearly that the magnitude of shear strain as a forced pressure was greater than supra- and infratentorial pressure.

The descent of the tentorial edge with an increase in the pressure gradient began in the initial stage of increasing intracranial pressure. It is assumed that the pressure gradient would be made smaller by the descent of the tentorial edge, and that the gradient progressively increased after the descent of the tentorial edge ceased. The edge of the tentorium may be elastic, until its descent has ceased. It becomes plastic like a strained string when the descent of the tentorial edge reaches its maximum. As soon as it becomes plastic, the edge of the tentorium may cause damage to the surrounding brain tissue and vessels. This is attributed to the change in physical characteristics from elastic to plastic. The dynamics of herniation should be considered as a stress-strain relation according to the elasticity in the brain substance at the edge of the tentorium.

The term “tentorial shear strain” is not, in a strict sense, a true shear strain. It actually means a force of strain at the edge of the tentorium only. Not withstanding a risk of oversimplification, the term “tentorial shear strain” is here used to describe a force of the hippocampal herniation through the tentorial edge.

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References


