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Effect of Head Position on Cerebrospinal Fluid Pressure in Cats: Comparison with Artificial Model

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Aim To demonstrate that changes in the cerebrospinal fluid (CSF) pressure in the cranial cavity and spinal canal after head elevation from the horizontal level occur primarily due to the biophysical characteristics of the CSF system, ie, distensibility of the spinal dura.

Methods Experiments in vivo were performed on cats and a new artificial model of the CSF system with dimensions similar to the CSF system in cats, consisting of non-distensible cranial and distensible spinal part. Measurements of the CSF pressure in the cranial and spinal spaces were performed in chloralose-anesthetized cats (n = 10) in the horizontal position on the base of a stereotaxic apparatus (reference zero point) and in the position in which the head was elevated to 5 cm and 10 cm above that horizontal position. Changes in the CSF pressure in the cranial and spinal part of the model were measured in the cranial part positioned in the same way as the head in cats (n = 5).

Results When the cat was in the horizontal position, the values of the CSF pressure in the cranial (11.9 ± 1.1 cm H_2O) and spinal (11.8 ± 0.6 cm H_2O) space were not significantly different. When the head was elevated 5 cm or 10 cm above the reference zero point, the CSF pressure in the cranium significantly decreased to 7.7 ± 0.6 cm H_2O and 4.7 ± 0.7 cm H_2O, respectively, while the CSF pressure in the spinal space significantly increased to 13.8 ± 0.7 cm H_2O and 18.5 ± 1.6 cm H_2O, respectively (P<0.001 for both). When the artificial CSF model was positioned in the horizontal level and its cranial part elevated by 5 cm and 10 cm, the changes in the pressure were the same as those in the cats when in the same hydrostatic position.

Conclusions The new model of the CSF system used in our study faithfully mimicked the changes in the CSF pressure in cats during head elevation in relation to the body. Changes in the pressure in the model were not accompanied by the changes in fluid volume in the non-distensible cranial part of the model. Thus, it seems that the changes in the CSF pressure occur due to the biophysical characteristics of the CSF system rather than the displacement of the blood and CSF volumes from the cranium to the lower part of body.

It has been shown in both animals and humans that changes in the intracranial pressure follow the changes in the head position (relative to the rest of the body). In a horizontal position, the values of cerebrospinal fluid (CSF) pressure are identical in both cranial and spinal parts of the subarachnoid space. However, elevation of the head from the horizontal position causes a drastic decrease in the cranial CSF pressure (1-3).

The cranial cavity is filled with the brain parenchyma, blood, and CSF. According to Monro-Kellie doctrine (1), these three volumes determine the intracranial CSF pressure. It is generally accepted that, when the head is above the heart level, the intracranial venous blood is redistributed to the lower parts of the body, whereby the venous vessels collapse (1,4,5) and intracranial CSF pressure decreases. It is also assumed that under such conditions, a part of the intracranial CSF volume flows into the spinal CSF space (6). Thus, the intracranial CSF pressure decreases and the intracranial compliance increases due to the changes in the intracranial blood and CSF volumes (7,8).

Our hypothesis was that the total volume of CSF and blood in the cranial cavity does not change during the head elevation because cranial osseous vault and dura mater, which is closely attached to the bones, prevent collapse of the intracranial space. On the other hand, because spinal dura mater is not closely attached to the vertebral column, the spinal CSF volume can change due to the distensibility of the dura (9,10). Thus, we presumed that decrease in the intracranial pressure during the head elevation may be a consequence of different biophysical characteristics of cranial and spinal CSF compartments.

To test our hypothesis, cranial and spinal CSF pressures were measured in cats during different position of the head with respect to the body. The results were compared with those obtained in an artificial model of CSF system similar to the CSF system in cats. This new model consisted of a non-distensible cranial part and distensible spinal part, which can change its volume.

Material and methods

In vivo study

The study was performed in 10 adult cats of both sexes (2.4-4.6 kg body weight). The animals were kept in cages with natural light-dark cycles and had free access to water and food (SP215 Feline, Hill's Pet Nutrition Inc., Topeka, KS, USA). The animals were in quarantine for 30 days and experiments were performed according to the Croatian Animal Welfare Act. The study was approved by the institutional Ethical Committee (Approval No. 04-76/2006-18).

The cats were anaesthetized with α-chloralose (100 mg/kg intraperitoneally [IP]) and fixed in a stereotaxic head holder (David Kopf, Tununga, CA, USA) in the sphinx position (Figure 1A). A stainless steal cannula (inside diameter [ID] of 0.9 mm) was introduced into a lateral ventricle at 2 mm lateral and 15 mm anterior to the stereotaxic zero point and 10-12 mm below the dural surface. According to the stereotaxic atlas of the cat brain, the distance between the position of cannula in the ventricle and foramen magnum is about 4 cm (11). The intraventricular cannula was used for the measurement of intracranial CSF pressures. To measure spinal CSF pressure in the lumbar region, laminectomy (5 × 10 mm) of L_3 vertebra was performed. After the incision of the spinal dura and arachnoidea, a plastic cannula (0.9 mm ID) was introduced into the subarachnoid space. Leakage of CSF was prevented by application of cyanoacrylate on the dura around the cannula. Bone openings in the cranium and vertebra were hermetically closed by application of dental acrylate. The cannulas for CSF pressure measurement were connected to pressure transducers (Gould P23 ID, Gould Instruments, Cleveland, OH, USA) and the sys-

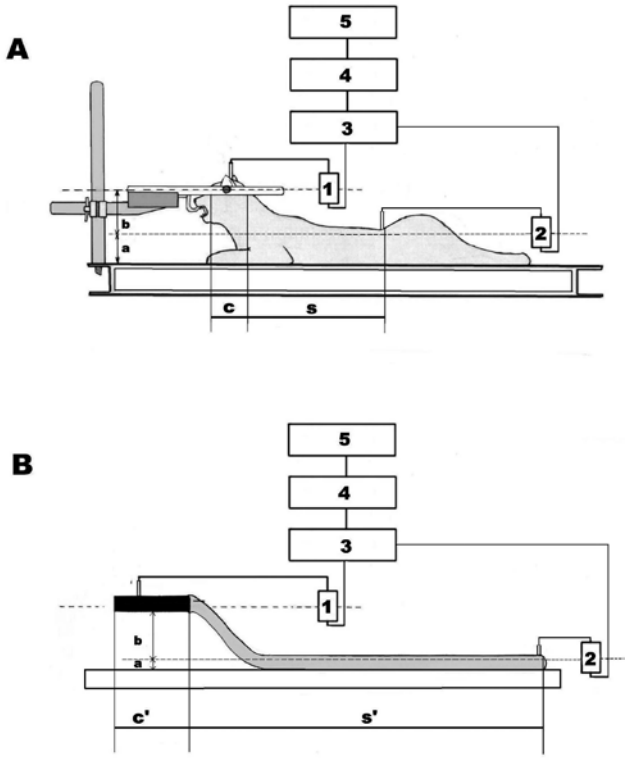

Figure 1. Scheme of the experimental model. Positions of cannulas in the cranial and spinal part of the cerebrospinal fluid (CSF) system in an experimental animal (**A**) and in the model (**B**). 1 – pressure transducer connected to the cannula in the lateral ventricle (A) or to the cannula in the cranial part of model (B); 2 – the pressure transducer connected to the cannula in the lumbar subarachnoid space (A) or to the cannula in the spinal part of model (B); 3 – Quand Bridge 4; 4 – PowerLab/800; 5 – personal computer; a – distance between the cannula in the spinal part of CSF system and ground level; b – distance between the cannulas in the spinal and cranial part of CSF system; c – cranial part of the cat's CSF system; s – spinal part of the cat's CSF system; c' – cranial part of the CSF system in the model; s' – spinal part of the CSF system in the model.

tem for transformation of analogous to digital data (Quand Bridge and PowerLab/800, AD Instruments, Castle Hill, NSW, Australia), and entered into a computer (IBM, White Plains, NY, USA).

Pressure transducers of both cannulas were calibrated by use of a water column; interaural line was taken as zero pressure. However, when the cat is in a horizontal position, the interaural line is 2 cm above the base of stereotaxic apparatus. When an artificial model is in a horizontal position, its horizontal midline is 0.3 cm above the base. To correct these initial hydrostatic differences, we introduced a distance "a", which was 2 cm for a cat and 0.3 cm for the model. We measured CSF pressures in a cat at the horizontal level (a+0 cm) and when the head was elevated 5 cm (a+5 cm) and 10 cm (a+10 cm). In the horizontal position, both pressure transducers were at the same level of the interaural line. When the cat's head was elevated for 5 cm (a+5 cm) or 10 cm (a+10 cm), pressure transducer for intraventricular pressure measurement was also elevated for the same vertical distance and therefore positioned at the same hydrostatic level as the interaural line (Figure 1A).

CSF system model

In the construction of the CSF system model, we took into account the anatomical dimensions and biophysical characteristics of the CSF system in cats. The cranial part of the model was made of a plastic, 6.0-cm long non-distensible tube with a diameter of 6.0 mm and wall thickness of 2.0 mm. The length of 6.0 cm corresponded to the distance in the intracranial cavity from the frontal sinuses to the foramen magnum, as found in 5 cats by x-rays of the animal skull. The spinal part of the model was made of a distensible rubber tube (natural rubber latex; Gemar, Casalvieri, Italy) with the outside diameter of 5.0 mm and wall thickness of 0.31 mm; its length of 31.0 cm corresponded to the distance between the foramen magnum and L_3 vertebra, where cannula was positioned in cats for spinal CSF pressure measurement. The model was filled with artificial CSF without the presence of air bubbles.

In the model, the cranial cannula was positioned in the plastic non-distensible tube 4 cm above the beginning of the distensible rubber tube, which corresponded to the distance be-

tween the cranial cannula and the foramen magnum in cats. The spinal cannula in the model was positioned in the distensible rubber tube 31 cm below the end of the cranial part of the model, which corresponded to the distance from the foramen magnum to L3 vertebra in cats.

Measurements of the fluid pressure in the model were performed at three different heights of its cranial part as follows: a+0 cm, a+5 cm, and a+10 cm. For the model a = 0.3 cm, which represents the distance between the base of the stereoaxic apparatus and the midline of the model when the model is in a horizontal position. This line is used as a reference zero point of pressure calibration for transducers (Figure 1B). The cannulas for the measurement of fluid pressure in the model were connected to the same system for data registration and retrieval as those for the fluid pressure measurements in the animals (Figure 1A).

Statistical analysis

Data were presented as means ± standard error of mean (SEM). Statistical significance of differences was determined by Student *t* test and by repeated measures analysis of variance (ANOVA). Statistical analysis was performed with Statistica 7.1 (StatSoft Inc., Tulsa, OK, USA). $P<0.05$ was considered statistically significant.

Results

When the cat was in the horizontal position (a+0 cm), there was no statistical difference between CSF pressures in the lateral ventricle (11.9 ± 1.1 cm H_2O) and lumbar subarachnoid space at L_3 vertebra (11.8 ± 0.6 cm H_2O) (Figure 2). However, when the cat's head was elevated 5 cm above the horizontal position (a+5 cm), the CSF pressure in the lateral ventricle decreased to 7.7 ± 0.6 cm H_2O ($P<0.001$), whereas the CSF pressure in the lumbar subarachnoid space increased to 13.8 ± 0.7 cm H_2O ($P<0.001$). Elevation of the head to 10 cm (a+10 cm) led to a further decrease in the CSF pressure in the lateral ventricle to 4.7 ± 0.7 cm H_2O, and further increase in the CSF pressure in lumbar subarachnoid space to 18.5 ± 1.6 cm H_2O. These changes were significantly different from the values obtained at a +5 cm ($P<0.001$).

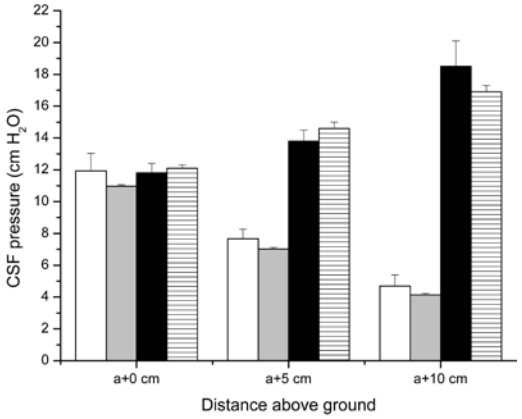

Figure 2. Effect of elevation of the cranial part of the cerebrospinal fluid (CSF) system on the CSF pressure (cm H_2O) in a cat and the model. CSF pressure (cm H_2O) in the cat's lateral ventricle (open bar; n = 10), in the cranial part of the model (gray bar; n = 5), in the cat's lumbar subarachnoid space (closed bar; n = 10), and in the spinal part of the model (striped bars; n = 5) at three different hights (a+0 cm, a+5 cm, and a+10 cm). For cats, a = 2 cm; for the model, a = 0.3 cm. Results are shown as mean value with standard error of mean (±SEM). There are no statistical differences (ANOVA; $P=0.600$) in pressures between the cat's CSF system and the model of CSF system at three tested positions (a+0 cm, a+5 cm, and a+10 cm).

Similar changes in the fluid pressure were observed in the cranial and spinal part of the model of CSF system (Figure 2). When the model was in the horizontal position (a+0 cm), the fluid pressures in its cranial (11.0 ± 0.1 cm H_2O) and spinal part (12.1 ± 0.2 cm H_2O) were not significantly different ($P=0.183$). When the cranial part of the model was elevated to 5 cm (a+5 cm), the pressure in it significantly decreased to 7.0 ± 0.1 cm H_2O and significantly increased to 14.6 ± 0.4 cm H_2O in the spinal part ($P<0.001$). When the cranial part of the model was elevated to 10 cm (a+10 cm), the pressures noted in the cranial (4.1 ± 0.1 cm H_2O) and spinal (16.9 ± 0.4 cm H_2O) part of the CSF system showed the same direction of changes as at a +5 cm position, with significant difference in the pressure

values at these two elevation points (P<0.001). When the pressures obtained at the same positions in cats and in the model were compared by ANOVA, no significant difference was found between them either in the cranial or spinal part (P=0.600).

Discussion

Our new model of the CSF system faithfully mimicked the changes in the CSF pressures in cats. In cats, the ventricular CSF pressure decreased and lumbar CSF pressures increased as the head was elevated to 5 cm (a+5 cm) and 10 cm (a+10 cm) above the horizontal position (a+0 cm). Similar changes in pressures were observed in the cranial and spinal part of the model when its cranial part was elevated. There were no statistical differences between the pressures at the same hydrostatic level in cats and the model.

Previous models of CSF system consisted of a rigid long tube closed from either both or one end by distensible materials (12). Such models failed to recognize main biophysical differences between the cranial and the spinal part of the CSF system in vivo. It is known that, in contrast to the cranial part, the spinal part can significantly change its volume (13-15). In the cranial cavity, the dura mater is closely connected to the bone, so cranial subdural space cannot change its volume. On the other hand, the spinal dura is only partly attached to the vertebral column, while its largest part is separated from the vertebrae by epidural space filled with fat tissue and venous plexuses. Thus, the spinal subarachnoid CSF space can expand or contract (13-15). For example, changes of CSF volume in the lumbar subdural space can be recorded during various physiological maneuvers (16), including increased pressure on the abdominal wall (17). Such changes of subdural volume are primarily enabled by the rich venous plexus in the epidural space, which can be filled or emptied depending on the exposure to various pressures (18,19). Magnetic resonance imaging shows that thoracolumbar CSF volume can be changed by 40%, depending on abdominal pressure: increased abdominal pressure leads to accumulation of venous blood in the epidural plexus and increase in the blood pressure, and consequently to the decrease in the thoracolumbar CSF volume (17). The spinal dura is stretched to a maximum in longitudinal direction, but it can be distended in perpendicular direction due to the arrangement of its elastic and collagen fibrils (9,10). The spinal CSF space can compensate for 30-80% of cranial pressure increase, as in case of brain edema, bleeding, tumors, or hydrocephalus, because of the distensibility of spinal dura and CSF displacement from cranial to spinal space (20,21). Thus, our model with the distensible spinal part and non-distensible cranial part seems to mimic faithfully the situation in vivo in cats.

Changes in pressures in our CSF model can be explained by the laws of hydrodynamics (22). When the cranial part of the model is elevated above the base of the stereotaxic apparatus, the pressure in the cranial part is decreased due to the downward pull of gravity. Such a gravitational "suction" lowers the pressure in the non-distensible cranial part of model. At the same time, the pressure in the spinal part rises due to the increase in the distance between the spinal cannula and "cervical" part of the model, ie, increase in the height of fluid column and consequent increase in the fluid pressure.

The pressure in the spinal part of the model does not increase as much as expected from the height of fluid column above the base. The spinal pressure in the horizontal position (a+0 cm) was 12 cm H_2O, whereas it was 17 cm H_2O in a+10 cm position. Thus, the pressure was increased only 5 cm H_2O while according to hydrostatic height a increase of 10 cm H_2O would be expected. This difference in the pressure can be ascribed to the distensibilty of the spinal part of the model, which can accommodate a larger fluid volume without the corresponding increase in the pres-

sure as if would if the model were non-distensible. The fact that the same spinal pressure changes were observed in both the model and the cats suggests that spinal dura mater behaves similarly to the distensible rubber tube used in the model. Since the cranial part of the model and the cranial cavity in cats are non-distensible, they obviously cannot change their total volumes. Thus, our results indicate that when the cat's head is elevated, the decrease in the intracranial pressure occurs due to the laws of fluid hydrodynamics rather than the displacement of the cranial CSF or blood to the parts of body with lower hydrostatic pressure as usually assumed. Observation that the gradient of pressure between cranial CSF and blood in dural sinuses does not change during different positions of head (23,24) support such interpretation of our data. Incompressibility of cranial osseous vault enables constant blood perfusion of brain despite sudden changes of head position in comparison to the body.

In conclusion, our results indicate that craniospinal CSF communication at foramen magnum enables maintenance of constant cranial CSF volume despite of changes of body position and CSF pressure.

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