The function of the cerebrospinal fluid space and its expansion

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Funkce likvorového prostoru a jeho expanze

Abstract

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In addition to its nutritive and protective effects, the basic function of the cerebrospinal fluid space resides in dynamic equilibration of pressure fluctuations caused by volume changes in three compartments contained within the rigid skull cavity: brain tissue, blood and cerebrospinal fluid.
An increase in volume in one of them brings about a compliant withdrawal in volume in the other two. The degree of cerebrospinal fluid compliance can be expressed by means of the pressure/volume index which is directly proportional to this compliance.
On the other hand an expansion of fluid space which forces the brain to withdraw its tissue, brings about the dilatation of brain ventricles. The degree of their dilatation depends on the effective pressure of cerebrospinal fluid which counteracts with the resistance of brain venous collectors. The blood in the venous network of the brain and cerebral extracellular fluid play a reversible role in cerebral mass restoration and reduction.
These facts explain the reason why, from the physical point of view, the brain is considered to represent a viscous and elastic spongious matter. *(Ref. 21.)*
Key words: cerebrospinal fluid space, expansion, compliance.

Abstrakt

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Základní funkci likvorového prostoru vedle nutritivního a ochranného působení cerebrospinální tekutiny je dynamické vyrovnávání tlakových výkyvů, které nastávají v důsledku objemových změn tří kompartmentů v uzavřené dutině lebky; mozkové hmoty, krve a likvoru. Zvětšením objemu jednoho z nich musí zbývající ustoupit. Stupeň ústupku, neboli kompliance likvorového prostoru, lze objektivně vyjádřit tlakovoobjemovým indexem, který je komplianci přímo úměrný.
Expanze likvorového prostoru, která si naopak vynucuje ústupek mozkové hmoty, se projeví rozšířením mozkových komor. Stupeň jejich rozšíření závisí na efektivním tlaku likvoru, proti kterému působí odpor v žilních kolektorech mozkové hmoty. Reversibilně se na úbytku a rekonstrukci mozkového pláště účastní žilní síť a extracelulární tekutina mozku. Proto se mozek z fyzikálního hlediska pokládá za viskoelastickou spongiózní hmotu. *(Lit. 21.)*
Klíčová slova: likvorový prostor, expanze, kompliance.

Cerebrospinal fluid space consists of two parts: cranial part formed by the cerebral ventricles and cerebral subarachnoidal space connected through the paired fourth ventricular foramina Luschkae, and the spinal part consisting of the spinal subarachnoidal space only connected to the cranial part by means of cisterna magna through the orifice of foramen Magendie of the fourth ventricle.

The cerebral subarachnoidal space is the most voluminous. It contains about 140 ml of cerebrospinal fluid. The spinal subarachnoidal space consists of about a half of this volume, approximately 60 ml, and brain ventricles contain 30 ml, therefore the ratio is 4.6:2:1. The cause is the rapid increase of the volume due to the increments of the circumferential layer. For example, when the radius of a sphere increases from 6 to 7 cm, the increase of the volume of this sphere is by 50 % (Nádvorník, 1983).

The real carrier of the functional significance of the cerebrospinal fluid space is the cerebrospinal fluid itself. From the functional point of view its role can be assessed from various angles, one mixed with another, even though one of them always prevails under certain circumstances.

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During the embryonic stage of the fetal development, the nutritive function is the most prominent. Till the third week, the cerebral cavities are filled in with fluid closely resembling extracellular fluid (Kapeller, 1991). It provides the nutrition for rapidly dividing neuroectodermal cells responsible for cerebral formation.

The fluid in the cerebral cavities named as physiological hydrocephalus (Filimonov, 1965) can be considered the developmental precedence of cerebrospinal fluid until the vascular network takes over the nutritive functions and the entire cerebrospinal fluid space is filled in with the definitive cerebrospinal fluid. However, it is justified to assume that CSF does not lose its nutritive functions even after the birth. This assumption is supported by the experience with embryonic neural tissue grafting when these grafts are able to survive in the ventricles until the connections with the acceptor vascular network form (Kolařík, 1990).

The process of cerebrospinal fluid formation takes place in the choroidal plexi of the cerebral ventricles, mainly lateral, as a result of the active transport of blood components through capillary walls and the surface cells of the choroidal plexus, in the average amount of 15 ml per hour (Hakim, 1976) and by means of cerebrospinal fluid cerebral pathways the fluid flows to cisterna magna, here it continues to fill in both cranial and spinal subarachnoidal spaces. Therefore cerebrospinal fluid forms a liquid mantle covering either the brain and spinal cord similar to a soft cushion forming a bed for neural structures. It implicates further functional significance of the cerebrospinal fluid and cerebrospinal fluid space as a protection coat. Under normal circumstances there is no direct contact between the hard inner surface of the skull and neural structures, but the brain does not completely freely drift in the cerebrospinal fluid. It is anchored in its position by means of arachnoidal stripes, trabeculae stretched between the arachnoidal membrane and pia mater that is fused to the superficial glial layer of the brain forming the pioglial membrane. The multiple anchoring "ropes" together with cerebrospinal fluid provides the hydrostatic stability for the brain. However, the arachnoidal membrane must also be supported. This support is ensured by the tightly closed subdural space similar to the lungs supported by negative intrapleural pressure.

From the mechanical point of view, the brain does not collapse after the violation of the arachnoidal membrane, because it contains an extensive vascular network, especially venous, together with neural pathways and cellular elements, and a huge extracellular space filled with tissue fluid.

The fluid from the subarachnoidal space is actively resorbed by means of arachnoidal processes. These processes, named as villi, were for the first time described by Harden in 1687, but the most famous name comes from Pacchioni (1741), according to whom these structures are known as Pacchioni's granulation taken for glands.

This problem was dealt by Retzius in 1875 and was described by convincing manners by Weed in 1923 when an evidence was created that this granulation was a flow pathway of the cerebrospinal fluid to the cerebral venous system. The arachnoidal villi form a connection between cerebrospinal fluid space and venous sinuses, mainly superior sagittal sinus.

The flow of cerebrospinal fluid absorption is unidirectional and works as energy-dependent active process. With the highest probability the regulation is provided by neuronal mechanisms. The arachnoidal membrane in the proximity of Pacchioni's granulation contains neural fibers described by Purkynje in 1831. These fibers originates from nerves passing through the arachnoidal membrane. All the cranial nerves are accompanied with dural and leptomeningeal sleeves having special significance in case of optic or vestibular nerves. Also the spinal roots at their entry point from the spinal canal are accompanied with dural or arachnoidal tubular or infundibular processes reaching the intervertebral foramen after passing shorter or longer distance.

Dura mater particularly inclines towards the perineural tissue, but the arachnoidal extensions reaches the neighboring tissue in a closed relationship with nerve. The contact lymphatic vessels is formed there (Schaltenbrand, 1955). The cerebrospinal fluid reaches the lymphatic system, and the venous system via the ductus lymphaticus. That is the reason why the cerebrospinal fluid space can be considered the lymphatic system of the brain and spinal compartments. Therefore Cushing used the term "third cerebral circulation" in 1925.

But the most important function of the cerebrospinal fluid space is to equilibrate the pressure differences appearing in the cranial cavity in a permanent manner. The intracranial volume consists of three parts, so-called compartments — brain tissue, blood and cerebrospinal fluid. The total cranial volume is about 1700 ml and consists of 1400 ml of cerebral tissue, approximately 100 ml of blood and the remaining 200 ml are filled with cerebrospinal fluid. The volume of the three compartments is not constant e.g. the blood compartment periodically changes with cardiac cycles conveying under the systole of about 10 ml of blood to the cerebral circulation or the return of blood from the head becomes more difficult if the breath is held up and this is how the cerebral compartment increases its volume (Rudinský, 1982; Hakim, 1992). In this case, the cerebrospinal fluid space acts as a sensitive dynamic regulation system. A well-known rule of Munro-Kelli (Marmarou, 1975; Rudinský, 1982) states that the volume increase of one or two compartments necessitates the retreat of the third one. Therefore in the situation when blood compartment or cerebral tissue compartment volume increases, the pressure is exerted on the cerebrospinal fluid compartment, which is the only one able to retreat. The cerebrospinal fluid as liquid is incompressible, but the elasticity of the dural sac of the spinal cord enables relocation movements of the fluid and equilibrium of pressure shifts caused by the changes of the remaining compartments can be balanced out (Rudinský and Nádvorník, 1982).

The cerebrospinal fluid space handles special regulation mechanisms that are associated with its retreat, compliance C, and formation and absorption of cerebrospinal fluid dependent on the outflow resistance R. The mathematical relation between the volume and pressure changes is exponential, and in logarithm scale the relation between the pressure and volume increments can be extrapolated as linear. This relation is known as a pressure-volume index:

$$PVI = \frac{\Delta V}{\Delta \log P}$$

The value of PVI expresses the volume in ml necessary to increase the intracranial pressure ten times. Under normal circumstances, its value is about 25 ml and the index is directly related to the compliance C and inversely to the pressure P:

$$C = \frac{0.4343xPVI}{P}$$

The compliance of cranial part of the cerebrospinal fluid space is about 68 % of the entire amount and therefore the spinal compliance is 32 %. If PVI index value is low, for example 5 ml, it means that 5 ml volume increment is sufficient to increase the opening pressure ten times, but it also means that the cerebrospinal fluid space can absorb only 5 ml volume increase.

Therefore compliance is the fundamental parameter characterizing cerebrospinal fluid space which is necessary to examine to be able to analyze the actual condition of regulation properties and to consider the role of neurosurgical procedure with the aim to reach the intracranial equilibrium. In the situation when the volume of the cerebrospinal fluid space increases, its expansion is present and the cerebral tissue retreats (Hakim, 1976). Under normal circumstances the pressure of cerebrospinal fluid in a patient lying flat varies between 70 to 180 mm of H_2O, and an equilibrium is formed with the volume of cerebrospinal fluid.

A shift towards the increase can be caused by the violation of the equilibrium between cerebrospinal fluid resorption and formation. The degree of resorption is therefore influenced not only by the pressure of the cerebrospinal fluid PCSF, but in the same way by the contra-pressure in the cerebral veins PV, its value usually being lower ranges around 70 mm of H_2O. The effective cerebrospinal fluid pressure is expressed by the equation:

$$P_E = P_{CSF} - P_V$$

Therefore the changes of the cerebrospinal fluid space volume and pressure can be influenced passively by the changes of cerebrospinal fluid drainage pathway resistance R, or actively by the change of the cerebrospinal fluid formation which affects the flow of cerebrospinal fluid.

If the cerebrospinal fluid pathways are not completely free, for instance in the case of aqaeduct stenosis or a tumor blocking the 4th ventricle, the cerebrospinal fluid pressure appears in the ventricular system of the brain resisted by the contra-pressure of cerebral tissue P_p, so the effective internal pressure of the cerebrospinal fluid inside the ventricular system PEI can be expressed by the equation:

$$P_{EI} = P_{CSF} - P_P$$

The P_P parameter consists not only of the venous pressure inside the brain parenchyma forming only 2 % of the cerebral volume, but also of extracellular fluid forming about 25 % of the entire brain tissue volume. The rest is represented by the resistance of the neural tissue consisting of lipids and proteins. Therefore the resistance of the cerebral tissue is the principal buffer acting against the effective pressure of the cerebrospinal fluid.

The compliance of the brain is achieved by such intracranial circumstances when the increase of cerebrospinal fluid effective pressure is present. In order to analyze the changes taking place inside the brain, Hakim (1992) proposed to apply the mathematical system created by Lamé in 1852, and Timoshenko and Goodier in 1934 for the pressure effects on the spherical homogenous and non-homogenous elastic bodies with central cavity. Due to the shape of the brain and skull certain degree of approximation is necessary, because neither the brain nor ventricles are spherical. But it is justified to take the brain for the viscoelastic non-homogenous spongious substance adopting to the pressure by means of volume changes. It undergoes an elastic compliance, the “loss”, and reconstitution as a result of mechanical compression of either cerebral nervous network and extracellular cerebral spaces in favor of the system of cerebral cavities and vice versa.

Also the tangential tensile strength of the brain tissue acts as a resistance against the effective pressure of cerebrospinal fluid. This tensile strength gradually decreases with the decreasing distance from the ventricular wall towards the subarachnoidal cerebral surface where the contra-acting radial tensile strength employs from.

Since the arachnoidal layer is narrow, its relationship with the dural surface is constant due to the anchoring arachnoidal trabeculae and the hard skull acting as an contra-pressure system.

That is the reason why the cerebral compliance originates in the vicinity of the cerebral ventricles. Either cerebrospinal fluid and extracellular tissue are compressed to their proximity. It is the result of pressure effects when the ventricular surroundings become the component of the cavity of brain ventricles and the dilatation of cerebral ventricles appears. If the equilibrium of tangential pressures takes a new level, then a new steady state of resorption and production processes form (Lorenzo, 1973). When the cerebral tissue during the pressure increase is influenced by the compliance, the picture of cerebral atrophy is observed and the resolution may be difficult.

However, if the compression is not powerful enough and the tangential radial strength is acceptable on a reasonable level, the reconstitution phase takes place together with the decrease of the effective pressure of cerebrospinal fluid which is most likely initiated by the radial tensile force of the brain. The “return” or reconstitution proceeds in the inverse direction compared to the “retreats” or compliance.

The situation is different when the skull sutures are not closed. The skull itself takes place in compliance formation. The circumference of the skull increases with the volume of the system of cerebral cavities. The brain tissue forms a spherical layer with decreasing thickness, however, since the diameter of the sutures increases with the growth of the head, the volume of cerebral tissue in constant in long term. Even under higher pressure more pronounced atrophy may not be present, because the limits of viscoelastic properties were not crossed.

The increase and decrease of ventricular volume take place as a compliance and the process of cerebral tissue reconstitution is controlled by the effective pressure of cerebrospinal fluid. However, elevated intracranial pressure can be caused by other parameters e.g. intraparenchymal brain tumors. Therefore the pressure-volume index should be related to the cerebral volume VB and the size of ventricles. The ratio is dimensionless, but the significance of this parameter is supported by the fact that if this parameter is equal to 1/2 or more, the cerebral tissue is no longer compressible in the reversible way. Spinal compliance is lower than the cerebral one. The increase of the pressure in dural spinal sac is equilibrated by means of its elasticity named as elastance.

The mechanisms responsible for the permeability of cerebrospinal fluid along the spinal roots have not been well-studied so far.

Conclusion

In the contrast to the past difficult pneumoencephalography the easy CT and MR examinations of the cerebrospinal fluid space are extensively employed. The borders of diagnostic and therapeutic possibilities have been broadened and these pathologies start to appear in the center of neurosurgical attention (Pernetzky, 1993' King, 1998). The process of the decisions on correcting the interventions requires the surgeons familiar with the actual function of the cerebrospinal fluid space to observe the function of dynamic regulation of pressure volume changes able to result in expansive behavior under pathological circumstances (Novák, 2000).

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