Review

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Quantitative and Qualitative Analysis of CSF Flow Dynamics

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ABSTRACT Disorders of cerebrospinal fluid (CSF) secretion, dynamics and absorption are common in different illnesses and injuries of the central nervous system (CNS). Nowadays magnetic-resonance tomography (MRI) is the leading research method of CSF dynamics. There are some MRI techniques for both qualitative and quantitative evaluation of CSF dynamic. The assessment of CSF movement is needed to define treatment strategy for patients with different types of hydrocephalus. In this review we have summarized the information about physic basement, area of application of modern MRI techniques. The main attention was paid to modern views on hydrocephalus pathogenesis, pathological CSF flow dynamics in CNS disorders and traumatic brain injury.

Keywords: cerebrospinal fluid, phase-contrast MRI, cerebrospinal fluid dynamics

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ICP — intracranial pressure
DPCC — diastolic phase of the cardiac cycle
MR signal — magnetic resonance signal
MRI — magnetic resonance imaging
RF pulse —– radiofrequency pulse
CSF — cerebrospinal fluid
SPCC — systolic phase of the cardiac cycle
CNS — central nervous system
TBI — traumatic brain injury
ASL — arterial spin labeling
ASSET — Array coil Spatial Sensitivity Encoding
CFD — computational fluid dynamics
FOV — rectangular-field-of-view
IR — inversion recovery
PC-MRI — phase – contrast MRI
ROI — region of interest
SNR — signal to noise ratio
SSFP — Steady-state free precession
TI — time inversion
Time SLIP — Time Spatial Inversion Pulse
TR — repetition time
VENC — velocity encoding
VPS — views per segment

PHYSIOLOGY OF CEREBROSPINAL FLUID DYNAMICS

Cerebrospinal fluid (CSF) is the main intrathecal biological medium circulating through the ventricular system of the brain, along the CSF pathways, subarachnoid space of the brain and spinal cord. CSF is a blood plasma filtrate and has a weak alkaline reaction. The main function of the CSF, which forms a water "cushion", is to protect the brain and spinal cord from external mechanical impact. Also, cerebrospinal fluid is an additional way of transporting various ions, molecules, proteins from the brain matter [1], [2].

The concept of CSF dynamics includes the following processes: CSF production, CSF circulation along the CSF pathways, and CSF reabsorption [3].

CSF FORMATION

According to the latest data, 80% of CSF is produced by the choroid plexuses of the cerebral ventricles which are a highly vascularized structure of epithelial cells. The process of CSF formation includes passive filtration of plasma from the capillaries of the plexus into the interstitial space of the plexus due to the pressure gradient; and then the filtrate is transported from the interstitial space to the ventricular cavity due to the activation of carbonic anhydrase and membrane transport proteins [3], [4]. Carbonic anhydrase catalyzes the formation of hydrogen ions (H^+) and bicarbonate (HCO_3^-) from water and carbon dioxide. The transport proteins of the basement membrane of the plexus change H^+, HCO_3^- for sodium (Na^+) and chloride (Cl^-) ions [5], [6]. Through the ion pump in the apical membrane, Na^+, potassium ions (K^+) and Cl^- enter the ventricular cavity [4]. Transport of water provided by aquaporin-1 of the apical membrane occurs due to the osmotic gradient provided by the ion pump [7], [8]. The Na-K-2Cl cotransporter of the apical membrane transports ions in both directions and is involved in the regulation of CSF secretion and composition [9].

The choroid plexuses also produce a number of other substances, such as vitamins B1, B12, C and folates. Some researchers suggest that they can affect the subventricular zone and participate in the restoration of tissues damaged by hydrocephalus [5].

The remaining 20% of CSF is produced through the system of interaction between CSF and the interstitial fluid of the brain [10]. Interstitial fluid fills the extracellular space between neurons and glia, cerebrospinal fluid fills the subarachnoid space and the ventricles of the brain. Communication between the two media occurs in the perivascular spaces surrounding the cerebral vessels that supply blood to the brain parenchyma [9].

The approximate CSF production rate is 0.4 ml/min, thus, approximately 500-600 ml of CSF is produced per day [11].

CSF secretion is regulated in several ways.

1. Due to the autonomous cholinergic, adrenergic, serotonergic and peptidergic innervation of the choroid plexuses of the ventricles. The sympathetic nervous system reduces the level of CSF secretion, while the parasympathetic nervous system increases CSF secretion. The autonomic nervous system is responsible for daily fluctuations in the level of CSF production [12].
2. By changes in the activity of carbonic anhydrase, aquaporins, and a membrane carrier protein (such as co-transporter Na-K-2Cl) in case of acid-base imbalance [12], [13].
3. Because of influence of some neuropeptide factors. The vascular plexus epithelium has receptors for dopamine, serotonin, melatonin, atrial natriuretic hormone, and vasopressin. Thus, the atrial natriuretic hormone, vasopressin, reduces the level of CSF secretion by affecting aquaporin 1 [12].

FEATURES OF CSF CIRCULATION

Transport from the ventricles of the brain, where the main part of the CSF is formed, to the subarachnoid space passes through the cavities and holes that form the CSF pathways. From the lateral ventricles, through the interventricular foramen (the foramen of Monro), the cerebrospinal fluid enters the third ventricle, through the cerebral aqueduct - into the fourth ventricle. From there, through the lateral foramen (of Luschka) and median foramen (of Magendie), CSF enters the basal cisterns of the brain and through the cisterna magna of the brain into the spinal space [14].

Before the advent of non-invasive neuroimaging techniques, it was assumed that the CSF flow was laminar, and the circulation was supported by the pressure differences between the cavities, the vertical position of our body in space, and the movement of the villi of the ependyma that lines the ventricles of the brain [14].

With the development of various imaging methods, a more detailed study of the CSF flow through the ventricular system of the brain became possible [3]. Thus, the unidirectional theory of the fluid flow was refuted with the development of phase-contrast magnetic resonance imaging (MRI) technology. In the first studies, the area of interest was the aqueduct of Sylvius, due to its central position in the ventricular system. Gated MRI made it possible to detect the bidirectional movement of cerebrospinal fluid through the aqueduct of Sylvius. In cardiac systole, the movement was noted in the caudal direction, in diastole - in the cranial

direction. With the further development of technology, a more detailed assessment of the CSF flow was made, and as a result the turbulent nature of the fluid flow towards the third ventricle was revealed. The same trend in CSF dynamics was soon found in the area of the foramen of Monro [14].

Another quantitative characteristic of CSF dynamics is the velocity of fluid motion. Already in1943, O'Connell suggested that the flow of cerebrospinal fluid is enhanced by the pulsation of the right and left thalamus, expanding during blood filling in systole, between which the third ventricle is located. Thus, the fluid flow velocity in the third and fourth ventricles is greater than in the lateral ventricles [15]. Further studies have shown that the pulsation of the epidural venous plexus in the cervical spine, which occurs due to changes in intrathoracic pressure during respiratory movements of the chest, also contributes to the acceleration of CSF flow in the subarachnoid space [16].

REABSORPTION OF CEREBROSPINAL FLUID

CSF reabsorption is understood as its reverse return to the venous bed. The main site of CSF reabsorption is the arachnoid granulations (pacchionian granulations) which are located convexitally along the superior sagittal sinus [17].

A large number of experiments have been carried out on the introduction of marker substances into the cerebrospinal fluid system to study the absorption process. As a result, it was suggested that there are alternative routes of CSF reabsorption, namely through the lymphatic system. This theory is currently controversial. During the experiments, it was found that a certain part of CSF can be absorbed into the CSF system through the perineural spaces of the cranial nerves. The significance of this path is not completely clear [17]. According to various sources, the proportion of reabsorption through the perineural spaces can be 5–40%.

The glymphatic system plays a significant role in the formation and absorption of CSF [5]. The major cerebral arteries are located in cisterns, channels containing CSF. At these levels, the arteries are covered by a pial sheath formed by leptomeningeal cells. Approaching the cerebral cortex, the arteries branch into the vessels of the pia mater. In the parenchyma, the arteries form penetrating arterioles which are surrounded by the perivascular space (Virchow–Robin space) [18]. This space is surrounded internally by the pial sheath and externally by the basement membrane of the astrocytic end-foot (glial limiting membrane). This system is called the glymphatic system, and in its function and structure it resembles the lymphatic system [19]. The glymphatic system is involved in the formation of the interstitial fluid of the brain, the sources of which are blood and CSF [1].

In most tissues, the transport of interstitial fluid occurs due to the difference in hydrostatic pressure which is created in the systole phase of the cardiac cycle [19]. In the brain, the transport of fluids and solutes is provided by the glymphatic system which includes a special system of aquaporin-4 channels [1].

CAUSES AND TYPES OF HYDROCEPHALUS

Hydrocephalus is a disease that is accompanied by an excessive accumulation of CSF in the ventricles of the brain and subarachnoid space. Clinical signs of hydrocephalus are rather nonspecific. These may include cerebral symptoms (headache, nausea, vomiting), diplopia, impaired concentration, gait disturbance, bladder dysfunction, and so on [20].

Hydrocephalus is caused by an imbalance between the production, transport and reabsorption of CSF [21]. Excessive accumulation of CSF leads to a breakdown of dynamic equilibrium of intracranial contents (blood, cerebrospinal fluid, brain matter) and an increase in intracranial pressure (ICP).

The first classification of hydrocephalus was proposed by W. Dandy in 1931. He divided hydrocephalus into two types - obstructive and communicating ones.

The cause for the development of obstructive hydrocephalus is impairment of CSF flow [22].

Obstruction at the level of the foramen of Monro causes unilateral ventriculomegaly. The most common causes of obstruction are glial tumors; ependymal, epidermoid, dermoid cysts; intraventricular hematomas.

The main causes of aqueductal stenosis are pineal tumors, gliomas, tentorial meningiomas, and vein of Galen–related aneurysms.

The cause of obstructed Luschka or Magendie is intraventricular hemorrhage, meningitis [23].

Narrowing of the CSF pathways in the area of the foramen magnum can occur due to osteochondrodysplasia, metabolic disorders, Arnold-Chiari malformation, syringomyelia and syringobulbia.

Acute hydrocephalus is possible after traumatic injuries of the posterior cranial fossa, intraventricular hemorrhages of traumatic and non-traumatic origin [24].

Obstructive hydrocephalus leads to increased ICP, which is an emergency situation requiring immediate action.

Another reason for the development of hydrocephalus is blocked or reduced CSF reabsorption. Traumatic subarachnoid hemorrhage causes damage to the ventricular cilia involved in CSF reabsorption [25]. Gradual restoration of cilia occurs after 30 days, which in turn in some cases leads to the restoration of CSF reabsorption. A history of subarachnoid hemorrhage increases the risk of developing hydrocephalus by 3 times during the first 2 years after injury [20]. Normal-pressure hydrocephalus is characterized by a progressive enlargement of the ventricular system against the background of normal ICP and the gradual development of clinical symptoms — the Hakim–Adams triad: gait disturbance, dementia, urinary incontinence [26]. Normal-pressure hydrocephalus can develop after intracranial hemorrhage, traumatic brain injury (TBI), and inflammatory diseases [1]. The main mechanism for the development of the disease is the occlusion of CSF reabsorption sites, the difficulty of transporting it into the blood.

ASSESSMENT OF CSF FLOW DYNAMICS USING MRI

MRI is the method of choice for the assessment of the CSF system of the brain and spinal cord, since it has a high diagnostic ability to detect both structural and functional disorders of the CSF flow [15].

The earliest MRI visualization of CSF flow was based on the detection of flow artifacts caused by high velocity characteristics and manifested by the loss of the MR signal on standard T2-weighted spin-echo images [27]. A quantitative assessment of the CSF flow was carried out based on the calculation of CSF relaxation times T1 and T2 and the determination of the degree of saturation between static tissues and moving CSF. Later, modified gradient sequences began to be used, in which the phase shift was induced by bipolar gradients built into the pulse sequence, which significantly improved the visualization of the CSF flow. For qualitative and quantitative assessment of CSF flow dynamics, cardiac-gated phase-contrast MRI is currently widely used [27]..

PHYSICAL PRINCIPLES OF PHASE-CONTRAST MRI

Phase-contrast MRI is based on the use of a bipolar magnetic field gradient, that is, a gradient with the same positive and negative magnitude and the same time of its application. Using one part of the gradient allows imaging of the fluid flow in one direction, so it is necessary to use both parts of the gradient in three planes to obtain a complete study. Phase-contrast MRI allows for both qualitative and quantitative assessment of the fluid movement. Thus, one of the main areas of its application in medicine has become the study of CSF flow [28].

The changing magnetic field creates a bipolar gradient that causes a phase shift to the moving spins. Spins moving in the direction of the bipolar gradient receive a positive phase shift, while spins moving in the opposite direction receive a negative phase shift. The number of phase shifts obtained is directly proportional to the fluid flow velocity and the time of application of the bipolar gradient.

Spins in a stable structure receive the same amount of negative and positive phase shift when a bipolar gradient is applied. Thus, the lack of movement, staying in the same position, obtaining the same gradient strength leads to zero phase shift. In every study using phase-contrast MRI, an image with zero phase shift is used as a reference image, which will subsequently be subtracted from the high-speed image. As a result, an image will be obtained only from moving spins [28].

The key parameter of phase-contrast MRI is VENC (velocity encoding), which is the encoding parameter for the velocities of spins moving in the flow [22]. From the point of view of physics, this parameter is understood as the speed at which a phase shift of 1 radian (180°) will occur. Incorrect selection of this parameter on the console of the MRI scanner significantly degrades the quality of the image obtained from the fluid due to an increase in the signal-to-noise ratio (SNR). The value of this parameter should be close to the actual values of the fluid flow, but not exceed it. Thus, for cerebrospinal fluid, this parameter is 5–20 cm/s (for example, in the region of the foramen magnum, the CSF flow velocity is 10 cm/s, in the area of the aqueduct it is 8 cm/s). However, in case of some pathological conditions, for example, stenosis of the CSF pathways, the VENC value should be chosen larger. Choosing an overestimated value of the VENC parameter can simulate the fluid flow in the opposite direction, which will lead to incorrect research results [29].

The lower the VENC value, the stronger the bipolar gradient must be applied for a longer time, which will increase the TR (repetition time) value. However, TR cannot increase indefinitely.

With phase-contrast MRI, magnitude and phase images are obtained. On the magnitude image, the CSF flow has a hyperintense signal, the signal from the "immobile" tissues is hypointense. The phase shift of the spins is encoded in the phase image. Accordingly, in case of the anterograde fluid flow, there will be a hyperintense signal, and a hypointense signal with the retrograde flow. Thus, the phase image carries information about the fluid flow velocity, which can be quantified.

Cardiac-gated phase-contrast MRI also allows evaluation of pulsatile fluid flow. This technique consists in receiving a signal from the fluid for several minutes, which is then averaged and synchronized with the heart rate [30].

To synchronize MRI data with the cardiac cycle, it is possible to use electrocardiography or digital plethysmography. Fluid flow information for each cardiac cycle is averaged at the end. This is why the phase-contrast MRI technique is insensitive to dynamic changes in the fluid flow [31].

The use of phase-contrast MRI has a number of limitations. First, the evaluation of such quantitative parameters as mean peak velocity, peak systolic velocity and stroke volume can only be measured in one plane perpendicular to the fluid flow. Accordingly, this technique will be ineffective in the study of the fluid flow inside arachnoid (subarachnoid) cysts, in the study of turbulent movement.

Secondly, in a phase-contrast study, a manual selection of a region of interest (ROI) is implied. The volume of the selected zone will affect such parameters as stroke volume, flow velocity, average peak velocity [32].

The phase-contrast study technique is associated with the patient's cardiac cycle and represents, as a result, averaged data obtained over a certain period of time.

EVALUATION OF THE FLUID FLOW GRAPH IN PHASE-CONTRAST MRI

The graph contains both positive and negative values of the fluid flow velocity. Positive values correspond to the cranio-caudal direction of the fluid movement and the systolic phase of the cardiac cycle (SPCC), while negative values correspond to the caudocranial direction and diastolic phase (DPCC) [33]. The maximum flow velocity in systole and diastole on the graph is indicated as "a" and "b", respectively. The space of the graph below peak "a" corresponds to the systolic volume of CSF, and the diastolic volume of CSF is above the peak "b" (Fig. 1) [34].

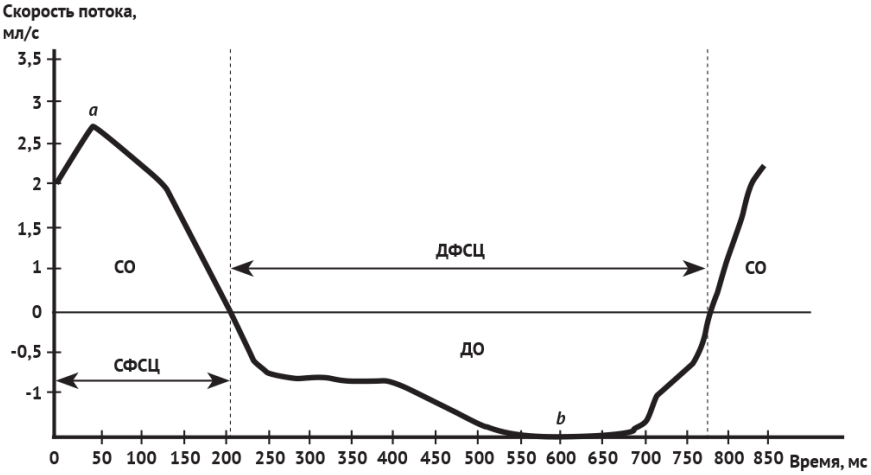

Fig. 1. Graph of cerebrospinal fluid flow associated with the cardiac cycle.
Notes: ДО — diastolic volume; ДФСЦ — diastolic phase of the cardiac cycle; СФСЦ — systolic phase of the cardiac cycle; СО — systolic volume. а — peak systolic velocity (cranio-caudal CSF flow); в — caudo-cranial CSF peak velocity during diastole

Japanese researchers proposed an improved method of phase-contrast study. Acceleration of the MRI technique was achieved by combining the methods of parallel imaging, rectangular field of view (FOV) and segmented k-space [31]. Parallel imaging using array spatial sensitivity encoding technique (ASSET) is based on the sensitivity encoding technique. This method allows data acquisition to be accelerated due to a so-called acceleration reduction factor by reducing the number of discrete phase encoding lines, although the

signal-to-noise ratio is somewhat reduced. Similar to parallel imaging, the rectangular FOV method can also reduce scan time by reducing the FOV phase encoding, i.e. reducing the number of selective phase encoding lines, although this also reduces the signal-to-noise ratio [35].

In the segmented k-space technique, the R–R interval of a cardiac cycle is divided into phases corresponding to k-space segments, and multiple k-space lines are built up during each cardiac cycle by reducing temporal resolution. Each phase of the cardiac cycle occupies one line (views per segment — VPS) of k-space. In the case of 2 VPS, the two k-space lines are filled sequentially during the cardiac cycle of k-space. As a result, the number of cardiac cycles required to complete k-space is halved, allowing information to be received twice as fast. In addition, this method makes it possible to reduce the scanning time without reducing the spatial resolution [31].

Most often, the phase-contrast technique is used to assess CSF flow dynamics in patients with arachnoid cysts and Arnold-Chiari malformation. Accurate knowledge of the anatomical structure of the arachnoid cyst and the type of its communication with the subarachnoid space allows planning the course of surgical intervention [36].

When planning a surgical intervention in patients with Arnold-Chiari malformation, it is necessary to study the CSF flow in the region of the craniovertebral junction. The phase-contrast method made it possible to evaluate the effect of multiple sclerosis on CSF dynamics [24]. In patients with multiple sclerosis, the volume of cranio-caudal and caudocranial CSF flow, as well as stroke volume, was higher [34].

PHASE-CONTRAST MRI IN THE EVALUATION OF CSF SHUNT OPERATIONS

The use of various MRI techniques makes it possible to evaluate the effectiveness of CSF shunt surgeries in patients with normal pressure hydrocephalus. A study by W. Bradley et al. (1996) showed that the significantly better effect after CSF shunt operations was in patients with a greater CSF stroke volume (more than 42 µl) [37]. In turn, M. Mase et al. (1998) found a larger amplitude of CSF flow in the cerebral aqueduct in patients with normal pressure hydrocephalus than with asymptomatic ventricular dilatation or brain atrophy. The amplitude of the flow is significantly reduced in the convexity subarachnoid spaces. The authors also revealed the relationship between the CSF flow velocity in the cerebral aqueduct and intracranial pressure. In patients with normal pressure hydrocephalus, CSF dynamics at the level of the cervical subarachnoid spaces remains within the normal range. With age, the elastic properties of the brain tissue decrease, and venous outflow decreases, but this does not lead to changes in the intracranial ratio. In patients with hydrocephalus, a slowdown in venous outflow, a decrease in pulsation in the convexital subarachnoid spaces, leads to CSF hyperpulsation in the ventricles [38].

Other researchers, when analyzing the surgical treatment of a large number of patients with hydrocephalus, did not reveal a relationship between CSF pressure and its peak flow velocity. The study also showed the relationship between CSF pressure and its average flow velocity. The authors conclude that the correctness of the ICP determination is largely affected by the magnetic field strength of the magnet used in the MRI machine. In 3T MRI machines and with a higher field strength, the noise level is significantly lower and a greater deviation of the VENC value is allowed than in scanners with a lower field strength, especially in case of a slow CSF flow rate [39].

In Russia, studies have also been conducted on the features of CSF flow dynamics in various diseases of the CNS. N.V. Arutyunov et al. (2016) examined a large group of patients who had disc herniations of various localizations, traumatic brachial plexus lesions and root avulsions, cysts filled with cerebrospinal fluid, empty sella syndrome, basal liquorrhea, congenital malformations of the brain, Arnold-Chiari pathology, obstructive hydrocephalus, open form of hydrocephalus and colloid cysts of the third ventricle. Some of the patients underwent triventriculostomy. The authors believe that phase-contrast MRI makes it possible to determine the qualitative and quantitative characteristics of CSF flow in various parts of the brain, which is necessary when determining the nature of hydrocephalus and pathology of the cerebral aqueduct (stenosis, occlusion, dilatation) [40].

FUNDAMENTALS OF THE TIME SLIP TECHNIQUE

Time-spatial Labeling Inversion Pulse (Time-SLIP) is a type of the ASL technique, the method of arterial spin labeling, which allows visualizing the dynamics of fluid movement by combining the selective and non-selective inversion recovery (IR) effects [41]. The non-selective IR effect is used to invert (flip) all proton spins

in the area under study, which become "tagged". In the time SLIP technique, the fluid itself is an endogenous marker; therefore, it is possible to obtain data from the fluid flow only until the radio frequency (RF) pulse is attenuated [42]. The spatially selective IR effect is used to invert all spins in the fluid under study repeatedly. As a result, after labeling the outflow of spins, an image is formed. The longitudinal magnetization of the spins outside the labeled region is restored, depending on the recovery time TI (TI - time inversion) of this tissue. Therefore, spins outside the labeled region are displayed as a low signal zone. The time to data acquisition, referred to as TI, performs two important roles: 1 - suppression of the signal from the background, 2 - marking the spins passing through the labeled region. This technique is recommended for visualization of several specific seconds of fluid flow, which makes it possible to visualize, for example, turbulent reflux flow between the aqueduct and the third ventricle (Fig. 2) [43]. The processes of obtaining an image using phase-contrast MRI and time SLIP techniques differ significantly and the resulting data cannot be directly compared.

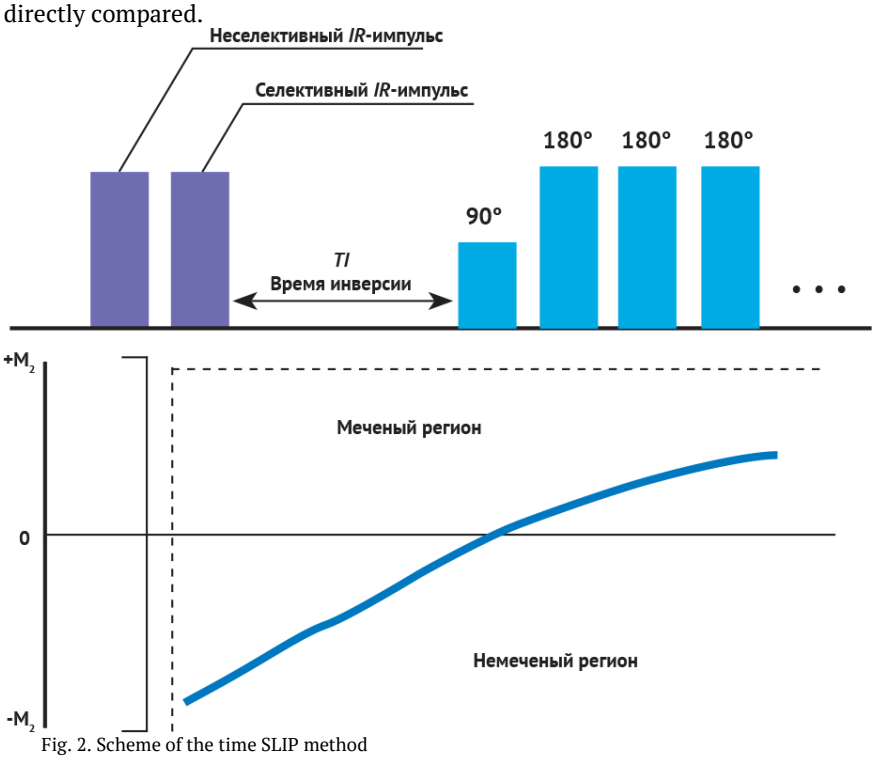

Fig. 2. Scheme of the time SLIP method

The use of the time SLIP technique allowed us to expand our knowledge of the pathogenesis of syringomyelia. With its help, several types of cerebrospinal fluid flow were recorded in the syringomyelia cavities: fast, “bubble”, “spasmodic”. Thus, the researchers suggested that the fast flow is formed due to a narrow obstacle, bubbles are created in the place of turbulent CSF flow, and the spasmodic flow is formed when passing through the arachnoid membrane and the septum of the syringomyelia cavity [44].

4D PHASE-CONTRAST MRI

Unlike 2D phase-contrast MRI, 4D phase-contrast imaging uses four-point scanning by measuring three-directional velocity encodings and one flow compensation encoding [45], [46].

Assuming that the background phase shift is the same in four different scans, the velocities in the 3 vector projection can be obtained by replacing the phase shifts in the 3 vector projection with the phase in the reference image [47], [48]. In a 4D phase-contrast study, three-vector volumetric phase images are usually used to reconstruct the flow velocity, one volumetric image of magnitude and 4 volumetric vector difference images (three-vector images and one summation image) to display the anatomy of the object of study (blood vessel, CSF pathways) (Fig. 3) [49], [50].

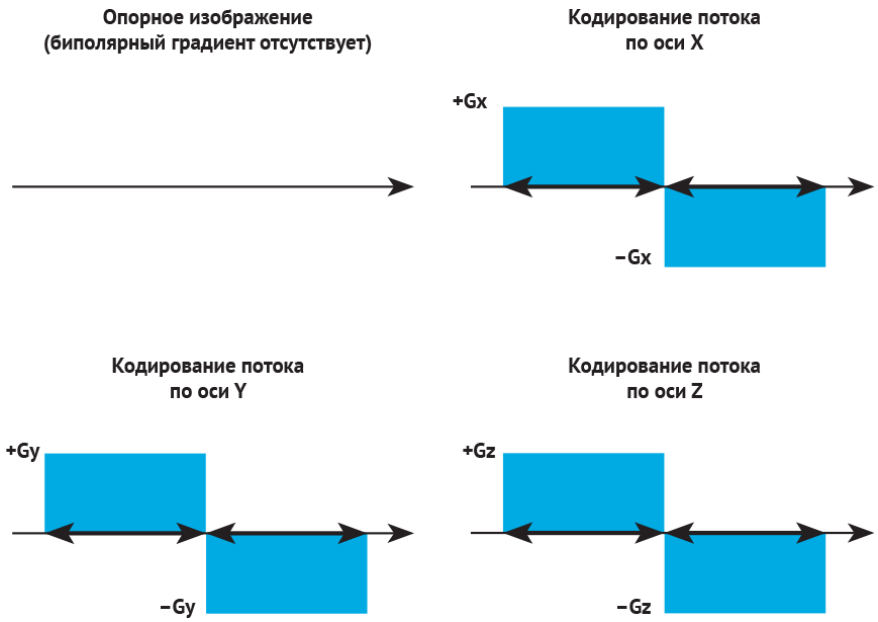

Fig. 3. Principle of 4D phase-contrast MRI

Despite the fact that obtaining a 3D image with the 4D phase-contrast study takes a lot of time compared to the conventional 2D phase-contrast study (PC-MRI), it has significant advantages, allowing you to examine the cerebrospinal fluid in any plane. In addition, 4D phase-contrast MRI, in parallel with obtaining a 3D image with high accuracy (comparable to a conventional 2D phase-contrast study), can determine the quantitative parameters of CSF flow dynamics. Quantification of CSF flow dynamics using 2D phase-contrast MRI may be inaccurate due to movements of the area under study (movement of the arachnoid membrane during the valve mechanism of hygroma formation), and 4D phase-contrast MRI can take into account the movement of areas of interest [42].

One of the promising methods for studying CSF flow dynamics is 4D phase-contrast MRI using computational fluid dynamics (CFD) techniques. The technique is based on mathematical modeling of the anatomy of the cervical spine based on 3D turbo spin-echo sequences with high T2 resolution. The 3D model was adapted to the actual anatomical dimensions. Reconstruction was performed separately for each level from the foramen magnum to the C7 vertebra. The CSF flow in the mathematical model was calculated using the Navier-Stokes equation. A comparative study of CSF flow dynamics in patients with Arnold–Chiari malformation showed the need to refine the method, in particular, taking into account fine anatomical structures, such as nerve roots and ligaments [51].

As a result, the obtained data of the two methods differed significantly. It is suggested that the deviation of CFD results from 4D phase contrast MRI measurements is likely due to the neglect of small anatomical structures in the cervical canal and tissue movement.

SSFP SEQUENCE

To diagnose the pathology of the CSF system, the SSFP sequence (Steady-state free precession) is also used, in which a nonzero steady state develops between pulse repetitions for transverse and longitudinal relaxation of the tissues under study. This requires a small angle of rotation and a short relaxation time. A feature of this technique is the ability to generate a strong signal in tissues that have a significant T2/T1 contrast, for example, CSF and adipose tissue [52]. Another advantage of SSFP sequences is a shorter scan time compared to other MRI sequences, which helps to eliminate CSF pulsation artifacts. Areas with turbulent CSF flow have a reduced signal (or even its absence). The disadvantage of this type of sequences is the low contrast resolution of soft tissues, the high sensitivity of the gradient echo pulse sequences to magnetic field inhomogeneity and the occurrence of various artifacts (for example, in the presence of metal, pronounced CSF hyperpulsation, tissue-liquid boundary zones, etc.). As for T2-weighted SSFP sequence, it may be difficult to differentiate between inflamed sinus mucosa and CSF accumulations, both of which have high signal

intensity. In addition, the image of major anatomical landmarks may be distorted due to submillimeter slice thickness. Thus, despite the static nature, this technique can be most effectively used in the diagnosis of skull base CSF fistulas, the assessment of the functioning of the ventriculostomy, however, in 8–10% of cases, this technique does not allow the detection of cerebrospinal fluid fistulas [53].

CHANGE IN FLUID FLOW DEPENDING ON THE TYPE OF HYDROCEPHALUS

When determining the CSF flow parameters among different age groups and between sexes, it was found that the velocity values of the CSF flow do not depend on gender, vary widely and differ significantly at different levels of the CSF system. It has been noted that peak linear velocities can be significantly increased in young people up to 14 years of age as a result of the high elasticity of the vascular wall. However, the mean linear and volumetric flow rates remained comparable to those in the middle age groups [54].

Also, using the phase-contrast MRI technique, the influence of body position on physiological processes in the cranial cavity was studied through the relationship between the dynamics of blood flow and CSF flow and their age-related changes [33]. With age, CSF pulsation weakens in proportion to the decrease in cerebral blood flow.

The advent of modern functional techniques has significantly expanded the diagnostic capabilities of MRI. Currently, the largest number of publications is devoted to the diagnosis of normal pressure hydrocephalus and its differential diagnosis with other types of senile dementia [22]. Much less research is devoted to the use of functional flow-sensitive MRI techniques (including the time-SLIP technique) in the diagnosis of various forms of obstructive hydrocephalus. Insufficient attention is paid to the pathogenesis of post-traumatic subdural hygromas, malabsorptive hydrocephalus after intracranial hemorrhages. Therefore, it is necessary to further study the possibilities of functional MRI techniques in the diagnosis of various types of hydrocephalus, as well as after surgical treatment.

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