HSR (LONDON),
HOUGHTON STREET REVIEW JOURNAL
ISSN: 2058-5519|Impact factor-15.9
http://houghtonstreetreview.com/index.php/hsr

INDIVIDUAL ANATOMICAL VARIANTS OF THE HUMAN BRAIN AND THEIR CLINICAL SIGNIFICANCE

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Abstract: Individual anatomical variants of the human brain are variations in the morphological structure within the physiological range, which are manifested at the level of the cerebral hemispheres, cortical folds (gyrification), cerebral ventricles, subarachnoid spaces, venous sinuses, and the arterial blood supply system. These variants are inextricably linked with embryonic development, genetic factors, postnatal neuroplasticity, age-related involutional processes, and individual somatic characteristics. Although individual anatomical differences are not considered pathology in most cases, they are of great importance in the process of clinical diagnosis from the point of view of differentiating them from signs of the disease, as well as minimizing anatomical risks during invasive procedures and surgical interventions. The configuration of the sulci and gyri of the cerebral cortex, asymmetry of the hemispheres, variants of the structure of the corpus callosum, individual differences in the size and shape of the lateral ventricles play an important role in interpreting the results of neuroimaging (CT, MRI, fMRI, DTI). In particular, the location variants of the Sylvian fissure, central sulcus, parietooccipital area, temporal folds and Broca-Wernecke areas are one of the factors explaining the different course of neurological symptoms, epileptic foci and clinical picture after stroke. At the same time, variants of the circle of Willis, hypoplasia or collateral branching of the anterior and posterior cerebral arteries have diagnostic and prognostic value in assessing the risk of ischemic stroke, aneurysm development and the likelihood of hemorrhagic complications. Therefore, a systematic study of individual anatomical variants of the brain and their clinically correct interpretation is of great scientific and practical importance in modern medicine in increasing diagnostic accuracy, reducing the number of misdiagnoses, strengthening the person-oriented (personalized) approach and ensuring the safety of surgical interventions.

Key words: brain, individual anatomical variants, morphological variability, hemispheric asymmetry, sulcus and gyrus, cerebral ventricles, circle of Willis, arterial variants, venous sinuses, neurovisualization, MRI, CT, clinical significance, differential diagnosis, neurosurgery.

Introduction. The structure of the human brain is biologically highly complex, and functionally it is the most delicate control system. As the main link of the central nervous system, the brain not only controls cognitive processes, memory, speech, emotions and movements, but also ensures homeostasis of the whole organism by coordinating vegetative functions. Therefore, in-depth study of the morphological structure of the brain remains one of the priority areas in the fields of anatomy, neurology, neurosurgery, radiology, forensic medicine and clinical diagnostics. In modern neurology and neurosurgery, not only the classical anatomical structure of the brain, but also its individual anatomical variants are of great scientific and practical importance. Because many differences observed in the structure of the brain can be clinically important even without being considered pathology. The concept of anatomical variants refers to individual differences in the shape and size of

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the cerebral hemispheres, the configuration of the cortical folds (gyri) and fissures (sulcus), the structure of the ventricular system, the subarachnoid space, the basal cisterns, the cerebral arteries and venous sinuses within the physiological range. These changes are explained by the individual genetic programming of neuronal migration, differential proliferation, gyrification dynamics, and vascular branching during embryonic development. The relevance of knowledge of anatomical variants of the brain in clinical practice is primarily associated with differential diagnosis. Since some variants may resemble pathological conditions in neuroimaging studies (MRI, CT, angiography). For example, slight asymmetry of the lateral ventricles, individual expansion of the subarachnoid space, differences in the level of development of the arachnoid cisterns or asymmetry of the venous sinuses in some cases increase the likelihood of confusing the diagnosis with hydrocephalus, atrophic processes, intracranial hypertension, tumors or venous thrombosis. Also, the location and degree of development of individual folds and fissures of the cerebral cortex play an important role in identifying epileptic foci, assessing signs of atrophy characteristic of neurodegenerative diseases, and accurately localizing the focus of a stroke. In recent years, the development of neuroimaging technologies has made it possible to study the individual anatomical features of the brain more accurately. High-resolution MRI modes, functional MRI (fMRI), diffusion tensor tomography (DTI), MR angiography and perfusion studies have expanded the possibility of identifying individual variability in the direction of brain structures and nerve fibers, as well as assessing anatomical correspondence with clinical symptoms. This has strengthened the personalized approach in medicine and increased the need for individualization of diagnostic and treatment strategies based on anatomical variants in each patient. In this regard, a systematic analysis of individual anatomical variants of the brain and their clinical significance will serve to increase the diagnostic accuracy of modern medicine, improve the criteria for differential diagnosis, ensure the safety of surgery, and provide a deeper understanding of the individual mechanisms of neurological diseases. This article analyzes the main types of anatomical variants of the brain, their manifestation in neuroimaging results, and their significance in clinical practice based on scientific literature.

Main part. The anatomical structure of the human brain is explained by general rules through classical definitions, however, the experience of practical anatomy and clinical medicine shows that in each human brain there are individual variants within the physiological range. These variants are manifested at the level of the configuration of the cerebral hemispheres, cortical folds and fissures, subcortical structures, ventricular system, basal cisterns, as well as the arterial and venous circulatory system. Although individual anatomical differences are often not considered pathology, the need for their correct interpretation in the process of clinical diagnosis and treatment is very high, which can lead to misdiagnosis, complications in invasive procedures, and increased surgical risks. The shape, size, and functional asymmetry of the cerebral hemispheres are among the most common individual differences in the human population. Hemispheric asymmetry is important not only morphologically (for example, the difference in size of the right and left hemispheres, the projection of the frontal or occipital poles), but also functionally (speech, memory, spatial perception, emotional processes). Anatomical and neuropsychological studies show that in most individuals, the dominance of the left hemisphere is associated with the location of the speech centers, while the right hemisphere is more dominant in spatial orientation and emotional processes. However, in clinical practice, this dominance is not a strict law: in left-handed individuals or patients with certain neuroplastic changes, speech zones can be located in the right hemisphere or bilaterally. This is of great importance in assessing the severity of post-stroke aphasia, the strategy for preserving functional zones during neurosurgical resection, and the localization of epileptic foci. Sulcus and gyrus (gyrification) of the cerebral cortex are one of the most important components of individual anatomical variants. The configuration of

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sulci, their depth, length, branching, and the presence of additional sulci vary significantly between individuals. The anatomical variability of the central sulcus, Sylvian fissure, precentral and postcentral gyri, superior temporal gyrus, and inferior frontal gyrus is of great importance for clinical neurology. For example, the projection location of Broca's and Wernicke's areas requires the use of FMRT and intraoperative cortical mapping methods, especially in epilepsy surgery or tumor resection. In some patients, the horizontal or oblique orientation of the Sylvian fissure, the thickness of the temporal operculum, or the degree of exposure of the insula change the surgical approach and increase the technical complexity of the surgery. At the same time, the strong development of gyrification or, conversely, a slightly simplified appearance can cause differential diagnostic problems in the assessment of cortical atrophy in neurodegenerative diseases. The size of subcortical structures - basal ganglia, thalamus, internal capsule, hippocampus and amygdala - also has individual differences. The shape of the hippocampus, its location in the medial temporal lobe, its border with the parahippocampal gyrus and differences in its internal architecture are of particular relevance in epileptology. The diagnosis of hippocampal sclerosis in temporal lobe epilepsy often relies on high-resolution MRI images. However, normal anatomical variants of the hippocampus (for example, slight rotation, asymmetric volume, width of the hippocampal fissure) can sometimes be confused with a pathological process. Therefore, in radiological interpretation, the individual range of the anatomical norm should be well understood. The ventricular system of the brain also has a wide variability in anatomical variants. Slight asymmetry of the lateral ventricles, elongation of their frontal or occipital branches, width of the atrium, shape and size of the third ventricle, as well as the configuration of the fourth ventricle are found in many healthy individuals. From a clinical point of view, these conditions require differentiation from hydrocephalus, intracranial hypertension, or atrophic processes. Especially in elderly patients, expansion of the subarachnoid space and an increase in the volume of the ventricles against the background of cortical atrophy may manifest as physiological involution. However, for differential diagnosis with normal pressure hydrocephalus, Alzheimer's disease, or other degenerative pathologies, it is necessary to evaluate the clinical symptoms and neuroimaging criteria together. Also, anatomical variants of the ventricular system are important in choosing a route and preventing complications during shunting operations or endoscopic ventriculostomy in neurosurgery. Individual differences in the basal cisterns and the subarachnoid space also play a role in clinical interpretation plays an important role in the diagnosis of cerebral infarction. The width of the perimesencephalic cisterns, the shape of the suprasellar cistern, the exposure of the Sylvian cisterns, as well as the degree of development of the tentorial cisterns are important in the diagnosis of subarachnoid hemorrhage, in cases of meningitis and meningoencephalitis, as well as in the assessment of the mass effect of intracranial tumors. In some cases, arachnoid cysts or segmental expansion of the cisterns are found as an incidental finding. However, when they coincide with clinical symptoms, they can be the cause of increased intracranial pressure, epileptic seizures, or focal neurological deficit. Therefore, it is necessary to analyze arachnoid cysts not only as a “variant”, but also based on clinical and radiological correlation. The arterial blood supply system of the brain is one of the most clinically significant areas in terms of individual anatomical variants. Hypoplasia, aplasia, or segmental developmental differences of the components of the circle of Willis are very common in the population. Variants such as hypoplasia of the anterior cerebral artery A1 segment, various configurations of the anterior communicating artery, the “fetal-type” appearance of the posterior communicating artery, and the degree of development of the P1 segment of the posterior cerebral artery determine the collateral possibilities of cerebral perfusion. Insufficient collateral flow can lead to an increase in the focus of necrosis during ischemic stroke, aggravation of clinical symptoms, and deterioration of rehabilitation outcomes. At the same time, variants of the circle of Willis are also

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considered a pathogenetic factor in the development of aneurysms, since the uneven distribution of hemodynamic flow increases arterial wall stress. The scientific literature has repeatedly noted that aneurysms are more common in the area of the anterior communicating artery, around the bifurcation of the internal carotid artery, and in the initial segment of the middle cerebral artery. Variants of branching of the middle cerebral artery (MCA), the number and direction of lenticulostriate arteries, as well as the degree of development of the anterior choroidal artery are important in the pathogenesis of stroke and in surgical practice. The perforating arteries supplying the basal ganglia and the internal capsule are very delicate and functionally important, and their damage can lead to severe hemiparesis, dysarthria, or permanent neurological deficits. Therefore, in neurosurgical operations, especially in the case of tumors, AVMs, or aneurysms in the basal ganglia, it is necessary to assess the individual vascular anatomy in advance by MR angiography or CT angiography. Variants of the vertebrobasilar system are also of great clinical importance. Asymmetry of the vertebral artery diameter, hypoplasia on one side, curvature of the basilar artery (dolichoectasia), changes in the branching of the posterior inferior cerebellar artery (PICA), and variants of the anterior inferior cerebellar artery (AICA) and superior cerebellar artery (SCA) can determine the clinical picture of brainstem and cerebellar ischemia. Vertebrobasilar insufficiency, dizziness, visual disturbances, ataxia, diplopia, and other symptoms may sometimes be exacerbated by vascular variants. However, clinical observations have shown that basilar artery dolichoectasia may be associated with cranial nerve compression, trigeminal neuralgia, or hemifacial spasm in elderly patients. The anatomy of the cerebral venous system also has high individual variability, which is often overlooked in neuroimaging practice. Asymmetry of the superior sagittal sinus, straight sinus, transverse sinus, and sigmoid sinuses is common in the population. In some individuals, the right transverse sinus is dominant, while in others, the left is dominant. Sometimes, a sharp narrowing or even complete absence of the transverse sinus on one side can be confused with venous thrombosis. The development of emissary veins is also clinically important: they can be a source of unexpected bleeding during surgery, as well as a route for the spread of infection from extracranial areas to the intracranial space. Variants of venous collectors require special attention, especially in operations on the posterior fossa, when resecting tumors near the sinuses, as well as when installing shunt systems. The clinical significance of individual anatomical variants is not limited only to diagnostics and surgery, but is also manifested in assessing the clinical course and prognosis of neurological diseases. For example, hemispheric asymmetry, individual features of cortical branching, and differences in the direction of nerve fibers determine the degree of recovery after a stroke, regression of aphasia, restoration of motor functions, and mechanisms of neuroplastic compensation hi may be one of the factors. Based on DTI studies, individual differences in the corticospinal tract, arcuate fasciculus, uncinate fasciculus and other major white matter tracts have been identified, and their relationship with clinical symptoms is being widely studied. This approach creates great opportunities, especially in identifying “functional risk zones” before neurosurgical resection, choosing a strategy to preserve important tracts near tumors, and improving operational outcomes. Brain anatomical variants also play an important role in forensic medicine. Not knowing the normal anatomical range when assessing intracranial hemorrhages, traumatic injuries, or congenital malformations can lead to erroneous expert conclusions. For example, there is a possibility that the individual width of the subdural space, the distribution features of the venous bridging veins, or the anatomical appearance of the arachnoidal cisterns may be confused with hematomas resulting from trauma. Therefore, anatomical variants should also be taken into account in medical examination practice. In modern clinical medicine, the study of individual anatomical variants of the brain is inextricably linked to the concept of personalized medicine. Anatomical differences in each patient allow for individualization of the

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ISSN: 2058-5519|Impact factor-15.9
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diagnostic algorithm, reduction of operational risks, optimization of treatment tactics, and more accurate assessment of the prognosis. In particular, in the practice of neurosurgery, interventional radiology, epileptology, stroke centers, and neurorehabilitation, sufficient knowledge of individual anatomy reduces medical errors and improves clinical outcomes. Thus, individual anatomical variants of the brain should be considered not only as a theoretical part of the science of anatomy, but also as an important diagnostic and prognostic resource of modern clinical practice.

Discussion. The issue of individual anatomical variants of the brain is becoming increasingly relevant in modern medicine, since a certain part of diagnostic errors, misinterpretations and complications in invasive procedures in clinical practice is associated with insufficient consideration of anatomical variability. Although anatomical variants in most cases fall within the range of physiological norms, their clinical significance is especially evident in the interpretation of neuroimaging results, neurosurgical planning, assessment of prognosis in diseases such as stroke and epilepsy, and selection of rehabilitation strategies. The first important point that attracts attention in the discussion is that anatomical variants of the brain should not always be considered as “incidental findings”. Because some variants, although not directly pathological, may appear in certain clinical situations as a risk factor or a background that exacerbates symptoms. For example, hypoplasia of the components of the circle of Willis, a “fetal-type” configuration of the posterior communicating artery, or a sharp asymmetry of the vertebral artery diameter may reduce the cerebral perfusion reserve, limit collateral blood flow during ischemic stroke, and cause the expansion of the necrosis focus. Therefore, it is advisable to pay special attention to stroke prevention, antithrombotic therapy strategy, and perfusion monitoring in patients with such variants. The second important issue is that the individual configuration of the folds and fissures of the cerebral cortex can complicate the localization of symptoms and the differential diagnosis process in clinical neurology. Although the sulci and gyri shown in classical anatomical atlases serve as a general guide in most individuals, in real clinical situations the location and branching of the central sulcus, Sylvian fissure, inferior frontal gyrus, or superior temporal gyrus vary significantly. This is especially important for the detection of epileptic foci, for mapping speech and motor areas using functional MRI, as well as for identifying “functional risk zones” in patients undergoing tumor resection. From this point of view, the concept of “individual functional anatomy” is gaining priority in neurosurgical practice over the “anatomical standard”. It is worth noting that the relationship between anatomical variants and clinical symptoms may not always be direct. That is, the same anatomical variant may be completely asymptomatic in one patient, but may cause clinically significant problems in another. Factors such as the patient’s age, blood pressure, atherosclerosis, diabetes, heart rhythm disorders, hypercoagulable states, history of trauma, or congenital connective tissue dysplasia play an important role in this. Therefore, not only a morphological approach is needed to evaluate individual anatomical variants, but also a complex clinical-etiopathogenetic approach. In general, individual anatomical variations of the brain should not be considered a “secondary” issue in clinical medicine, but rather an important determinant of diagnosis, treatment, and prognosis. In-depth study and practical application of anatomical variability will improve clinical outcomes in neurological and neurosurgical diseases, reduce the number of medical errors, and strengthen the person-centered approach to medicine.

Conclusion. Individual anatomical variants of the human brain represent the variability of the morphology of the central nervous system within the physiological range and are manifested at the level of the cerebral hemispheres, cortical folds (gyri) and fissures (sulcus), subcortical structures, ventricular system, basal cisterns, as well as the arterial and venous blood supply system. These variants are inextricably linked with embryonic development, genetic determination, neuronal migration, gyrification processes, postnatal neuroplasticity, age-related involutional changes, and

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individual somatic characteristics, and in most cases are not considered pathologies. Despite this, their clinical significance in modern medicine is increasingly increasing. The results of the analysis show that anatomical variants of the brain play an important role in interpreting the results of neuroimaging (MRI, CT, MR/CT-angiography, MR-venography, FMRT, DTI). In particular, the individual sulcogyral configuration of the cerebral cortex is of particular importance in the localization of epileptic foci, the assessment of cortical reorganization associated with tumors, the anatomical substantiation of post-stroke neurological deficits, and the identification of individual projections of functional zones. At the same time, asymmetry of the ventricular system, individual manifestations of the subarachnoid spaces and basal cisterns create the need for differential diagnosis with hydrocephalus, atrophy, intracranial hypertension, subarachnoid hemorrhage, or inflammatory processes. Anatomical variants in the arterial blood supply system, in particular hypoplasia or aplasia of the components of the circle of Willis, fetal-type configuration of the posterior communicating artery, asymmetry and dolichoectasia in the vertebrobasilar system, are considered as factors determining the cerebral perfusion reserve. These variants can play an important role in the pathogenesis of ischemic stroke, transient ischemic attack, aneurysm, and hemorrhagic complications. Also, anatomical differences in the venous sinuses and venous drainage system are associated with the risk of bleeding in neurosurgical practice, misinterpretations in the diagnosis of venous thrombosis, and difficulties in assessing the dynamics of intracranial pressure. In general, a thorough study and clinically correct interpretation of individual anatomical variants of the brain are necessary to increase diagnostic accuracy, reduce the risk of iatrogenic complications, individualize the surgical approach, and widely implement the principles of personalized medicine in practice. Knowledge of the anatomical variability of the brain improves the quality of clinical decision-making not only in anatomy and radiology, but also in the fields of neurology, neurosurgery, epileptology, stroke medicine, forensic medicine, and rehabilitation.

The following scientific and practical proposals were developed based on the article:

1. Individualization of neuroimaging protocols: It is recommended to comprehensively evaluate anatomical variants of the brain using methods such as high-resolution MRI (3T and above), MR angiography, MR venography, perfusion MRI/CT, and DTI. Especially in cases related to stroke, epilepsy, tumors, and aneurysms, the combined analysis of vascular and functional anatomy increases diagnostic accuracy.

2. Improvement of radiological interpretation standards: In order to prevent conditions such as ventricular asymmetry, sulcus configuration, venous sinus hypoplasia, and individual appearance of basal cisterns from being incorrectly assessed as “pathology” during the diagnostic process, it is necessary to reasonably apply the concept of “anatomical variant” in radiological conclusions and clearly define differential diagnostic criteria.

3. Prioritizing functional anatomy in neurosurgical planning: It is recommended to use FMRT, DTI-tractography, and intraoperative neuromonitoring in patients undergoing tumor resection, epilepsy surgery, or invasive procedures for cerebrovascular pathologies. This approach allows preserving functional zones against the background of individual sulco-gyral variants.

4. Strengthening the “variant anatomy” block in medical education: In medical schools and residency programs, it is necessary to introduce separate training modules on MRI/CT anatomy, angiographic variants, venous drainage maps, functional anatomy, and individual anatomical variability, along with classical anatomy.

5. Incorporating annotations on anatomical variants into clinical protocols:

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Incorporating recommendations on the clinical interpretation of anatomical variants and their role as risk factors into national and local clinical protocols for stroke, epilepsy, aneurysms, hydrocephalus, and intracranial tumors will reduce diagnostic errors.

6. Expanding scientific research: Population studies of individual anatomical variants of the brain and their clinical consequences, analyses based on multimodal neuroimaging, as well as scientific research aimed at studying the relationship between genetic and epigenetic factors are promising areas.

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