Assessment of Structural and Topographic Characteristics of Meningiomas from the Standpoint of Surgical Treatment Tactics

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A high risk of damaging critical neurovascular structures arises at the attempt of radical meningiomas elimination. Partial removal of the tumor reduces the risk of intraoperative losses, but inevitably increases the recurrence rate. Palliative operations preserve the quality of patient's life, but make them victims of repeated operative interventions.

The aim of the investigation was to define structural and topographic characteristics of meningiomas of various locations from the standpoint of surgical treatment tactics.

Materials and Methods. Analysis of the author's own data on treatment of meningiomas in Nizhny Novgorod Interregional Neurosurgical Center has been carried out. 127 patients, aged 20–73 years, received surgical treatment in the period from 2000 to 2014, have been examined. The follow-up period covered from 2 months — to 7 years.

Results. Based on the knowledge of tumor structural integrity, meningioma's fractal patterns have been identified. Various types of its structure are determined by meningioma's internal properties and realize in the process of their growth. Two models of meningioma growth have been suggested. Diverse surgical tactics of tumor removal, minimizing probable operative losses, have been considered.

Conclusion. The principle of meningioma structural analysis, taking into account peculiarities of its structure, growth and topography, allows the surgeon to plan and realize an adequate surgical tactics, minimizing the intensity of operative complications.

Key words: meningioma; structural tumor analysis; neurosurgical tactics.

Meningioma is one of the most widely spread primary tumors of the central nervous system. Morbidity rate amounts to about 7 cases per 100,000 people [1–4]. Despite the essential progress in neurosurgical technologies of the recent time, radical elimination of meningiomas is not possible in all cases, especially when they are located in craniobasal regions [5–7]. Radicality of tumor removal at the expense of expanded surgical accesses results rather often in worsening of life quality due to cosmetic and neurological deficit. Introduction of stereotaxic radiosurgery into the complex of treating patients with meningiomas is restricted by its vicinity to neurologically important structures, diffuseness of its spreading over the dura mater, and often by its cost. One should agree, that radiosurgery as a method of "removing tumors without surgery" only limits, at best, its development [2, 6].

Two types of meningiomas are described in the literature: nodular and infiltrative, when the tumor grows into the surrounding tissues and extends along them [1, 3, 4]. Multiple meningiomas may be presented by a combination of infiltrative and nodular forms [2, 3]. And invasive character of the tumor growth does not correlate with its histological characteristic, speaking of complicated interrelations of the tumor and the body [3, 4]. These tumors invade the extracranial areas, for example, ethmoidal and paranasal sinuses, infratemporal fossa, and other anatomical regions. Surgically, the most difficult meningiomas are located in the medial parts of the skull, they infiltrate the structures of the cavernous sinus, sphenopetroclival area, medial parts of the temporal pyramid, the Turkish saddle diaphragm, overgrow the great vessels of the internal carotid artery and the area of its adjacent branch.

The aim of the investigation was to define structural and topographic characteristics of meningiomas of various locations from the standpoint of surgical treatment tactics.

Materials and Methods. An observation group included 127 patients aged 20–73 years (the average age 49 years), who underwent surgical treatment in Nizhny Novgorod Interregional Neurosurgical Center for "meningiomas of various location" from 2000 to 2014.

The study complies with the Declaration of Helsinki (the Declaration was passed in Helsinki, Finland, June, 1964, and revised in October, 2000, Edinburg, Scotland) and was performed following approval by the local ethic committee. Written informed consent was obtained from every patient.

The average age of pathological process manifestation was 47.0±9.7 years. A wide implementation of MRT and CT imaging techniques in the region made it possible to diagnose meningiomas prior to the appearance of the first signs and symptoms

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of the disease in 11 patients. As a rule, the reason for examination was cephalgic syndrome in hypotension disease and cerebral atherosclerosis. These patients formed a group with concurrent cerebral pathology. The terms between the onset of meningioma and the first clinical symptoms are difficult to establish. Manifestation of the disease in middle ages, i.e. 40–50 years, is rather typical [1, 3–5]. According to our observations the majority of patients saw the surgeon 2–3 years after the first clinical manifestation of the disease, having MRI and/or CT confirmation of the lesion, which makes the problem of searching new ways of reducing the time of early diagnosis urgent. And at the same time, such situation speaks about a slow growth of the tumor.

All patients underwent clinical and neurological investigations, MRT and/or CT of the brain with contrast enhancement, neuro-ophthalmological and otoneurological examinations. Control CT investigations were performed in the early postoperative period — within 10 days, and if hemorrhage was suspected in the tumor bed it was done as required. Instrumental diagnosis of meningiomas, based on radiological imaging techniques (CT and MRT) enables the surgeons to assess meningioma extension, the character of bone tissue changes, the character of growth, availability of secondary changes in the form of cysts, hemorrhages, petrificates, presence of pathological vessels in the tumor. Functional status of the patients before and after operative intervention was evaluated using Karnovsky score [8].

All 127 patients were operated on, including 23 reoperated persons due to the continued growth and intracranial extension of meningiomas. All operative interventions were accomplished under general and endotracheal anesthesia.

Radicality of tumor resection was determined on the basis of intraoperative assessment and findings of MRT and/or CT investigations.

Data were statistically processed using Statistica 6.0 program (StatSoft Inc., USA). To assess the significance of differences between the patients' functional status before and after the operation nonparametric Wilcoxon test was used. The difference was considered statistically significant at $p<0.05$.

Results. Of 127 operated patients 12 cases were reoperated for partial removal of meningiomas, besides in 7 of them the tumor infiltrated cavernous sinus and circularly covered internal carotid artery. Manifestations of ischemic cerebral circulation disorders at the level of the tumor were found preoperatively in one patient, and intraoperatively intimate intergrowth of meningioma and a vessel wall with its thinning and destruction were revealed. Here the tumor itself served as a "wall" of the vessel. In 3 cases there was noted extension of the tumor to the ethmoidal sinus from the primary point of growth, located in a lesser wing, where transformation of the surrounding tissues into hyperosteous changes of the sinus bone septa took place. This type of tumor extension increased greatly the technical difficulties of performing the operation and the risk of postoperative nasal liquorrhea. In 1 patient residual tumor was left at the tentorium margin backward from the tentorial foramen, whereto the wall of the beginning of the straight sinus is projected.

Hemorrhagic complications appeared in 8 patients out of 127: hemorrhage in the tumor bed (7 patients), secondary hemorrhagic impregnation into the tumor remnants in the area of the posterior cranial fossa (1 patient). The most frequent complication was liquorrhea (5 patients) — both nasal and from the skin suture. In 3 individuals secondary meningoencephalitis developed concurrently with pneumonia.

Motor or mixed sensomotor aphasia was observed in 3 out of 24 patients with the location of the tumor in the motor speech zone. Stable ischemia in one brain hemisphere with a clinical picture of gross and stable hemiparesis developed in a woman with a giant meningioma of a lesser and greater wings of the main bone and circular tumor growth on the medial cerebral artery.

In all patients with convexital meningiomas complete or partial regression of the focal symptoms in the postoperative period was noted. An average score of the operated patients' condition at the time of discharge equaled to 70±10 points (from 50 to 80 points) according to Karnovsky performance score, which did not differ significantly from the preoperative period ($p>0.05$).

Histological findings speak of the predominance of typical meningiomas (stage I) in 89% of cases, atypical and anaplastic meningiomas (stage II, III) comprise 11%. Patients with cell atypia found in histological examination were referred to oncological settings for chemotherapy treatment in the early postoperative terms.

Discussion. To improve the quality of the operative surgery in meningiomas spatial structure of the tumor was studied in terms of its fractal assessment, principal model of the growing tumor was created, analysis of tumor–brain topographical and anatomical interrelations was carried out.

Spatial structure of meningioma. The following structural components are typical for a common meningioma: hyperostosis; thickening of the cerebral dura mater, on which the basis of the tumor is located; tumor itself; tumor capsule adjacent to the brain tissue; areas of tumor-induced brain edema. The signs of malignancy manifest themselves in the alteration of the tumor shape, infiltration of the surrounding tissues and membranes, bone and aponeurosis, extension of the tumor to sinuses (Figure 1).

Method for assessing the degree of tumor atypia, confirmed by the following histological investigations, has been developed by us. It is based on the calculation of fractal dimension. A fractal is a mathematical set possessing the property of self-similarity, i.e. uniformity in various measurement scales. Having taken the form of meningioma surface as a basis of our calculations, we have estimated, that "irregularity" of its surface increases in tumor anaplasia. This is confirmed in the course the operation and by preliminary CT/MRT investigations. Depending on the value of the complex number *Zo*, the

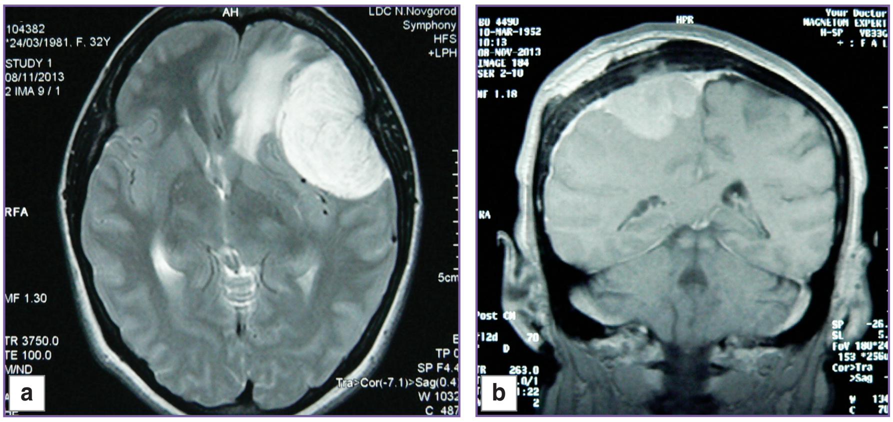

Figure 1. Examples of meningiomas with various degree of invasion into the surrounding tissues: (a) typical structures; (b) malignant type of the structure

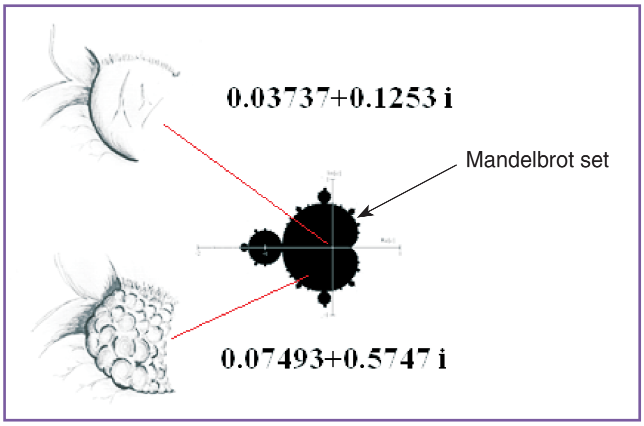

Figure 2. Comparative similarity of different meningioma shapes and fractal set

simplest iterative formula *Zn=Zo+C*, corresponding to the Julia set, will define the similarity of meningioma shape in 2D plane, either by the data of CT or MRT investigations (Figure 2). Approximation of two meningiomas with different structures using fractal models shows, firstly, their qualitative structural difference, and secondly, which is more important, fundamental distinction of formation and growth processes. Consideration of meningioma structural atypia is useful in respect to the choice of tactics of the operative approach to the planning and performing operative manipulations.

Following such analysis, a surgeon can conceive the tumor in its integrity and unity.

Model of the growing meningioma. We have assumed, that it is better to describe growth and development of meningiomas by means of hydrodynamic model. It clearly explains formation of some components present in the tumor of this type, i.e. distribution of tissue density in the tumor itself, and generation of hyperostosis on the internal surface of the bone. Considering the property of body movement (a ball) in a viscous fluid (Figure 3), some similarity of flow characteristics of the moving ball (evident asymmetry of the flow streamlining the ball is seen) and meningioma growth structure can be noticed. Streamlining a ball, according to the Helmholtz model, generates a track — an area of fluid at rest. Thus, a real model must consider the flow resistance and flow separation from the body. In relation to meningioma, there may be assumed the existence of pressure difference on its surface adjacent to the brain tissue (P1), and pressure of "separation" at the site of adherence to the bone (P2), with P1>P2. Thinking in this way, the origin of a sickle-shaped induration zone in the apical part of meningioma, and, most important, the cause of forming bone hyperostosis at the site of the tumor primary growth can be explained.

"Spatial metamorphosis", which sets various geometrical forms of one and the same tumor with a histologically identical structure, realizing in a certain individual, is the condition that proves the functionality of the suggested model of meningioma structural areas. No doubt, convexital and basal meningiomas are different, but the principle of their formation remains identical.

With a great portion of theoretical approximation Reynolds criterion can be applied for mathematical calculations of the growing meningioma behavior. This criterion (Re) is the relation of inertial forces, acting in the flow, to the viscous forces:

$$Re=(\rho \nu D_r)/\eta,$$

where ρ is medium density (kg/m^3); ν is speed of

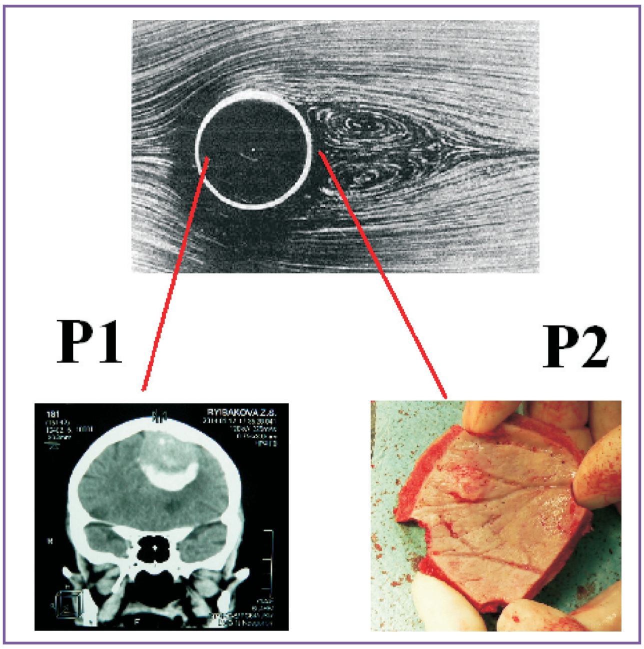

Figure 3. Hydrodynamic model of meningioma growth, explaining availability of some of its structural features

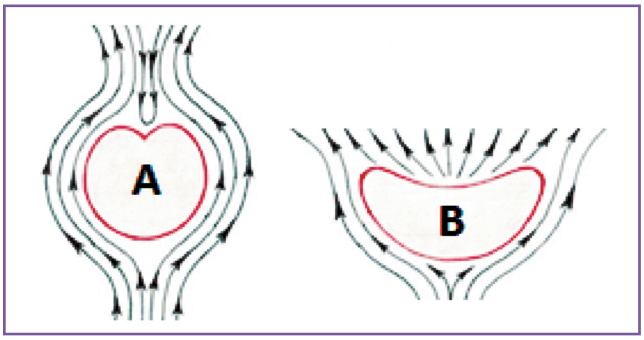

Figure 4. The model of flow generation in slow-growing (*A*) and rapidly growing (*B*) meningioma

movement (m/s); D_Γ is hydraulic diameter (m); η is dynamic viscosity of the medium (H·s/m²).

Density of the brain tissue (or medium) and dynamic brain viscosity are invariable parameters in the formula. Therefore, Reynolds criterion value is determined by the speed of the tumor growth, which is very slow, and the surface area, getting in touch with the brain in the process of its growth (variable parameter). The mathematical model should meet the following requirements: there must be a solution, its unicity and stability. In our case the existence of some solution arises from the comparison of slow-growing benign and rapidly growing malignant meningiomas according to the data of the rough calculations using Reynolds criterion. In case of a slow-growing tumor the growth speed is low, the hydraulic diameter, reflecting the area of tumor and brain contact, increases slowly, the values of Reynolds criterion are also low. In rapidly growing meningioma the speed of the tumor growth is much higher, the hydraulic diameter also increases quicker, and Reynolds criterion values are higher. It is known, that at a low Reynolds criterion the solution of the equation describes a "radial current" flow directed to the center of the moving body; at a sufficiently great values of Re nonstationary, separating motion may appear (Figure 4). Such distribution of the flow in the first case promotes formation and growth of hyperostosis of the adjacent bone, while in the other case it results in infiltrative tumor growth along the cerebral dura mater and bone destruction.

The developed model presents, for the first time, a tumor as a moving substance with various kinematics.

Surgical treatment of meningiomas. Approach to surgical treatment of meningiomas, especially those with craniobasal localization, is described in numerous works [1, 5, 6, 9, 10]. In our opinion, there are three major directions of surgical management of meningiomas, depending on its three basic localizations: convexital, growing into the sagittal sinus and craniobasal. It is impossible to disclose all peculiarities of the operation in a single article, therefore, to elaborate the tactics of surgical manipulations it is necessary to follow the basic principles of intraoperative assessment of meningioma. They include: access to the supplying vessels (evaluation of inflow and outflow of blood from the tumor, the type of ingrowth and/or displacement of great vessels); density properties of the tumor itself; stroma intensity; interrelations with the structures of adjacent brain and spare liquor spaces.

The sequence of removing *typical convexital meningioma* in the process of the operation after targeted craniotomy consists of the following stages (Figure 5):

a) determining the projection of the meningioma extension center;

b) semicircular resection of the brain dura mater along the tumor margin leaving the "vascular" pedicle in the projection of convexital veins, flowing into the sagittal sinus — it leads to ischemization of the tumor itself and minimizes blood loss during its elimination;

c) partial tumor removal to reduce traumaticity of the brain by its volume decrease; then the adhered arachnoidal membrane on the tumor border is dissected and separated microsurgically from the tumor;

d) final removal of the tumor and homeostasis, dura mater defect plasty.

Succession of removing *meningiomas located on the basis of the skull* is different. It is impossible to remove sphenopetroclival and some craniobasal meningiomas without damaging the nerves and vessels, involved in the process. There are no strict recommendations concerning surgical decisions to be made. Manipulations in the area of tumor–nerves contact are fully individual. The situation differs essentially, for example, when an optic nerve is displaced by the tumor with its tension, intergrows with the tumor capsule, the optic nerve canal zone is circularly overgrown by the tumor which extends along it. The structurally important parts (the nerve, great vessel, pituitary stalk) appear in the depth of the neoplastic process, and moreover, in the zones of intensive blood flow, such as cavernous sinus, superior orbital fissure, superior and inferior petrosal sinuses, jugular foramen. When identification of these structures is difficult, preservation of a tumor part will be the last choice. The surgical actions in this situation should be oriented to the maximal reduction of blood flow directed to the tumor remnants along the vessels of the dura mater.

Planning the tactics of *basal meningiomas* surgery is based on pre- and intraoperative examination of their projection on the skull base, pioneered by the author. The projection of basal meningioma on the base of the skull, as we understand it, is the method, which is based on visual perception, when all common points or points of contact of the tumor and the skull base are projected to the tumor itself developed on a plane. Projection of a basal meningioma is obtained by projecting the whole tumor surface onto the horizontal plane. Lambert azimuthal equal-area projection is the prototype of this method. Thus, using the method of combining and exclusion of two projections, the central projection of a tumor and points of its contacts with the base are finally obtained. The scheme of generating projection of multiple points of the tumor surface and base onto the X line in the frontal section is shown on Figure 6.

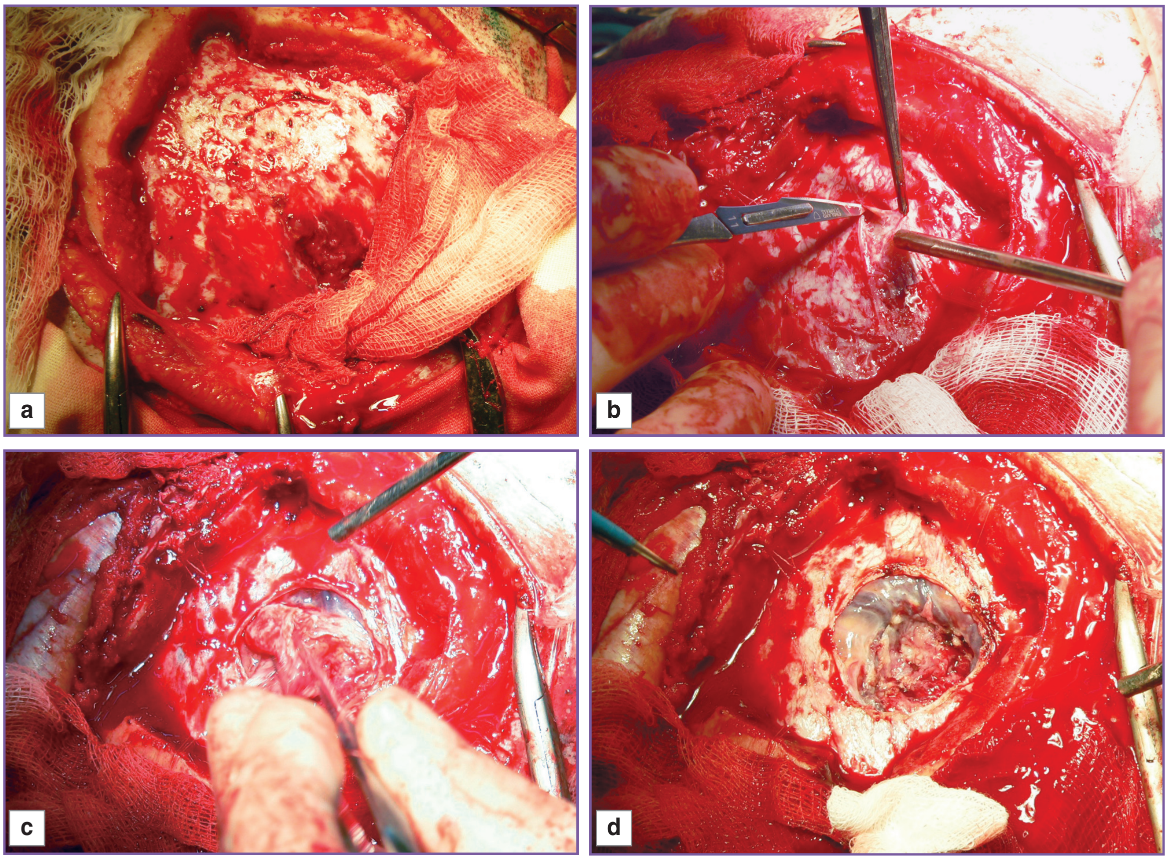

Figure 5. Stages of removing convexital meningioma

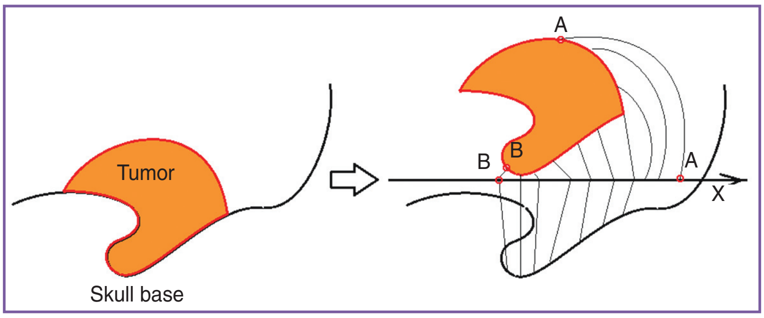

Figure 6. The scheme of generating projection of multiple points of the tumor surface and base on X line

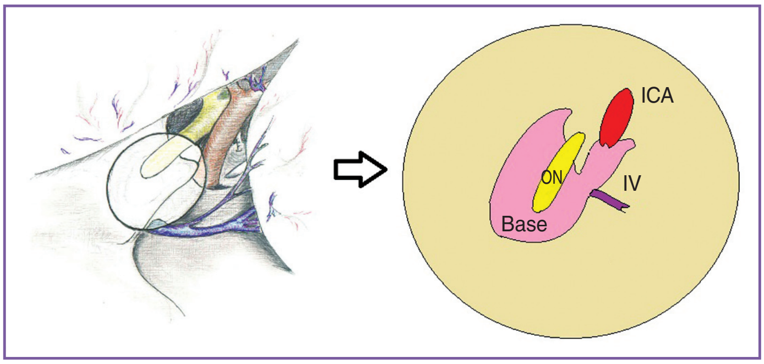

Figure 7. Projection scheme of meningioma position. ICA: internal carotid artery; IV: internal vein; ON: optical nerve

As the result there appeared a scheme, showing the interrelation of the tumor and the skull base (Figure 7), where projection of the zone of meningioma ingrowth on the base, the main structural components into which the tumor grows and overgrows, are presented. Using this scheme, the following major stages of the operation on the base tumor removal may be outlined.

Dura mater is dissected linearly and basally along the access base, when the brain is well relaxed, the state which in some cases is achieved by a dosed lumber liquor drainage (in a marked edema there may be necessary to use mannitol and additional dissection of the dura mater). Methods of dura mater dissection may be diverse. In basal meningiomas we recommend epidural approach to the tumor margin, if it is accessible. In that case dura mater dissection is performed along the margin of the adjacent dura mater to the maximal accessible depth.

The approach to the tumor margin is made subdurally, a target coagulation of the margin of its transition to the dura mater — within the zone accessible at this stage. According to the projection scheme this is the first stage of

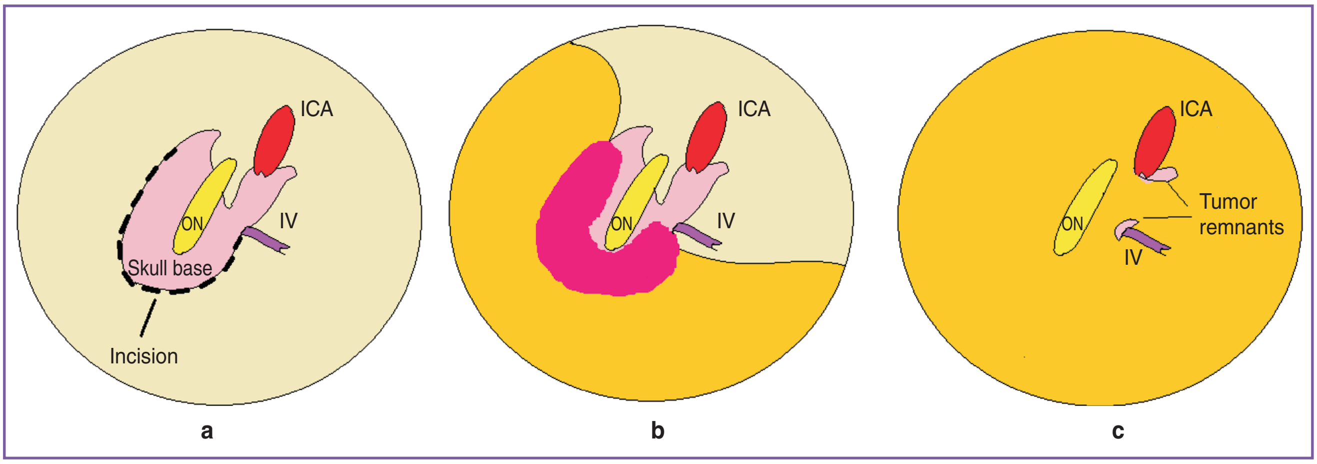

Figure 8. Stages of removing skull base tumor according to the projection scheme. ICA: internal carotid artery; IV: internal vein; ON: optical nerve

the approach to the basal menigioma. On Figure 8 (a), the technique of dura mater dissection along the tumor margin is shown by a dotted line.

The capsule is dissected and partial removal of the tumor masses is performed trying to create internal decompression. Here attention should be paid to the fact, that a part of the tumor with its capsule, adhering to the brain, is used by us for brain protection (Figure 8 (b)). This is the principal moment of the surgical manipulation.

Having achieved significant internal decompression by removing the main tumor volume, simultaneous cutting off the main vessels supplying the tumor, is done. The access to the skull base is created via the tumor "window".

Manipulations on the remnants of the skull base tumor is the next stage of surgical intervention (Figure 8 (c)). A microscope is then adapted to the surgical tasks, directed to the separation of the nerves and release of the vessels. It should be noted, that nerves are usually displaced, and interrelations between the tumor and vessels may be different. In some cases the tumor capsule grows into the great vessel, and sometimes the vessel wall is replaced by the tumor masses.

At the final stage, tumor remnants, adjacent to the brain and protecting it from traction at the previous stages, are eliminated.

Thus, a long-term growth with various clinical and neurological presentations, depending on localization and secondary tumor manifestations, is characteristic for meningiomas. The presented work was attempted to show those morphological changes, which take place in the process of tumor growth. The nature of these changes remains obscure so far. In our work we tried to present a tumor as an integral structure, which forms according to its own strictly determined and often unclear peculiarities. Invasive growth into the skull base makes some meningiomas, located near neurovascular structures, difficult for removal, with a high probability of neurological complications, limiting the extent of permissible resection. Performance of a planned non-radical resection is a central issue solved in the process of operation. Considering the character of meningioma structure generation as an integral formation allows the surgeons more adequate planning and performing operative treatment.

It should be mentioned, that the tactics of surgical management of meningiomas has changed significantly in recent years: simple invasion into the tumor via the shortest access and the following active removal of the tumor by pieces is now avoided; method of circular dissection of dura mater has been introduced to the surgery in convexital meningiomas; craniobasal meningiomas have been resected in a strict succession of manipulations. All this improves the quality of operative treatment.

Conclusion. Investigations of meningioma structure as a voluminous process and application of the suggested principles of the analysis in the operative work minimizes essentially operative losses.

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