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LONG-TERM FUNCTIONAL OUTCOMES OF NEODYMIUM LASER-ASSISTED RESECTION OF BASAL AND PARASAGITTAL MENINGIOMAS

Abstract. Basal and parasagittal meningiomas represent some of the most surgically challenging intracranial tumors due to their close relationship with major venous sinuses, cranial nerves, and functionally significant brain structures. The absence of a unified surgical strategy, particularly in cases involving invasion of the superior sagittal sinus, contributes to a high incidence of postoperative neurological deficits and tumor recurrence. The present study aimed to evaluate the long-term effectiveness of neodymium laser-assisted microsurgical techniques in the resection of basal and parasagittal meningiomas by assessing cerebral hemodynamics and electroencephalographic parameters in the late postoperative period. A total of 389 patients operated on between 1995 and 2009 were analyzed more than five years after surgery. Patients were divided into a comparison group treated with standard microsurgical methods and a study group in which neodymium laser technology (wavelength 1.064 μm) was used at key stages of tumor resection. Long-term outcomes were assessed using electroencephalography and transcranial Doppler sonography. Laser-assisted surgery was associated with a higher rate of radical tumor removal, lower postoperative mortality, better preservation of cerebral blood flow, and a significantly lower frequency of pathological EEG changes, including midline structure dysfunction and epileptiform activity. These findings indicate that neodymium laser technologies reduce surgical trauma and improve long-term functional outcomes in patients with complex basal and parasagittal meningiomas.

Keywords: meningioma; parasagittal meningioma; skull base tumors; neodymium laser; electroencephalography; transcranial Doppler sonography.

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ОТДАЛЁННЫЕ ФУНКЦИОНАЛЬНЫЕ РЕЗУЛЬТАТЫ УДАЛЕНИЯ БАЗАЛЬНЫХ И ПАРАСАГИТТАЛЬНЫХ МЕНИНГИОМ С ПРИМЕНЕНИЕМ НЕОДИМОВОГО ЛАЗЕРА

Аннотация. Базальные и парасагиттальные менингиомы относятся к числу наиболее сложных для хирургического лечения опухолей головного мозга вследствие их тесного анатомического контакта с верхним сагиттальным синусом, магистральными сосудами, черепными нервами и функционально значимыми структурами мозга. Отсутствие единой хирургической стратегии, особенно при инвазии опухоли в верхний сагиттальный синус, обуславливает высокую частоту послеоперационных неврологических дефицитов и рецидивов заболевания. Целью настоящего исследования явилась оценка эффективности применения

неодимового лазера при удалении базальных и парасагиттальных менингиом на основании анализа показателей мозговой гемодинамики и электроэнцефалографии в отдалённом послеоперационном периоде. Проанализированы отдалённые результаты хирургического лечения 389 пациентов, оперированных в период с 1995 по 2009 гг., со сроком наблюдения более 5 лет. Пациенты были разделены на группу сравнения, оперированную стандартными микрохирургическими методами, и исследуемую группу, в которой использовались лазерные технологии на основе неодимового лазера с длиной волны 1,064 мкм. Применение лазерных технологий обеспечило более высокую радикальность удаления опухоли, снижение послеоперационной летальности, лучшее сохранение показателей мозгового кровотока и достоверное уменьшение частоты патологических изменений ЭЭГ, включая признаки дисфункции срединных структур и эпилептиформную активность. Полученные данные подтверждают клиническую эффективность и патофизиологическую обоснованность использования лазерных технологий при хирургическом лечении менингиом сложной локализации.

Ключевые слова: менингиома; парасагиттальная менингиома; опухоли основания черепа; неодимовый лазер; электроэнцефалография; транскраниальная доплерография.

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BAZAL VA PARASAGITTAL MENINGIOMALARNI NEODIM LAZER YORDAMIDA OLIB TASHLASHNING UZOQ MUDDATLI FUNKSIONAL NATIJALARI

Annotatsiya. Bazal va parasagittal meningiomalar bosh miya o'smalari orasida jarrohlik jihatdan eng murakkab guruhlardan biri hisoblanadi. Bu ularning yuqori sagittal sinus, asosiy qon tomirlari, bosh miya nervlari va funksional ahamiyatga ega tuzilmalar bilan yaqin anatomik aloqasi bilan bog'liq. Ayniqsa, yuqori sagittal sinus invaziyasi mavjud bo'lgan holatlarda yagona jarrohlik strategiyasining yo'qligi operatsiyadan keyingi nevrologik asoratlar va qaytalanishlar xavfini oshiradi. Mazkur tadqiqotning maqsadi bazal va parasagittal meningiomalarni olib tashlashda neodim lazer texnologiyalarining uzoq muddatli samaradorligini miya gemodinamikasi va elektroensefalografik ko'rsatkichlar asosida baholashdan iborat.

1995–2009 yillarda operatsiya qilingan va kamida 5 yil kuzatilgan 389 nafar bemorning uzoq muddatli natijalari tahlil qilindi. Bemorlar standart mikrojarrohlik usullari qo'llanilgan solishtirma guruh va neodim lazer (to'lqin uzunligi 1,064 mkm) ishlatilgan asosiy guruhga ajratildi. Lazer yordamida bajarilgan jarrohlik amaliyotlari o'smalarni yanada radikal olib tashlash, operatsiyadan keyingi o'lim ko'rsatkichlarini kamaytirish, miya qon aylanishini yaxshiroq saqlash hamda EEGda patologik o'zgarishlar, jumladan, o'rta chiziqli tuzilmalar disfunktsiyasi va epileptiform faollikning kamroq uchrashini bilan tavsiflandi. Ushbu natijalar murakkab lokalizatsiyadagi meningiomalarni jarrohlik yo'li bilan davolashda neodim lazer texnologiyalarining yuqori klinik samaradorligini ko'rsatadi.

Kalit soʻzlar: meningioma; parasagittal meningioma; bosh miya asosidagi oʻsmalar; neodim lazer; elektroensefalografiya; transkraniyal dopplerografiya.

Introduction. Meningiomas, tumors of the meningovascular series, account for 18 to 35.8% of the total number of primary brain tumors in adults; in terms of incidence (an average of 7.44 cases per 100,000 people), they are second only to tumors of the neuroectodermal series [8–10, 12]. Women suffer from meningiomas 2.2 times more often than men, an average of 10.02 and 4.44 cases per 100,000 population, respectively [8, 9, 12, 14]. Parasagittal and basal meningiomas are the most difficult to remove due to the anatomical features of growth. The incidence of parasagittal meningiomas (PSM) ranges from 20.5 to 40.0% of all meningiomas of the cerebral hemispheres. They are diagnosed at the skull base in 45% of cases [3, 5, 10, 12]. Currently, the literature data indicate the absence of a surgical standard for the treatment of SCI with damage to the superior sagittal sinus (SSS). These meningiomas, located in the middle third of the sinus, are the most difficult to remove due to the abundance of afferent veins, the frequent occurrence of severe neurological deficit after surgery and the high risk of recurrence [7, 10]. In 28.8–47.5% of cases, patients have a severe neurological deficit after surgery, and 18.6% of patients from the total number of operated patients remain profoundly disabled [3, 6]. Today, there is no clear surgical strategy for meningioma invasion of the SSS. Radical surgery for SCI is possible only in cases of small marginal damage to the SSS [3, 11]. In this regard, a higher incidence of their continued growth and recurrence is noted compared to meningiomas of any other localization, reaching 50% depending on the observation period [9, 11]. The problem of surgical treatment of basal meningiomas is also far from being completely resolved. This is due to the slow growth of meningiomas, a long, sometimes asymptomatic course of the disease, which is why patients are admitted to hospital with neoplasms of large, and sometimes gigantic sizes. Basal meningiomas often arise in anatomically difficult to access areas of the brain and are in close contact with the main arterial vessels, cranial nerves and functionally important structures. These circumstances predetermine the difficulties in their total removal [6, 8, 11]. During resection of these neoplasms, it is not always possible to radically remove their matrix and underlying hyperostosis due to its inaccessibility, as well as the high risk of opening the air sinuses and subsequent technically complex reconstructive surgeries. As a result, the degree of radical tumor removal decreases, which often leads to disease progression. The recurrence rate depends on many factors, primarily on the radicality of meningiomas' removal and their histological structure, and reaches 40% with an observation period of at least 10 years from the date of surgery [6, 12, 13]. Thus, The problems of surgical treatment of these tumors are far from resolved and remain relevant worldwide. These circumstances stimulate the development of new concepts and technologies for the resection of cerebral meningiomas, ensuring improved clinical treatment outcomes, maintaining a high quality of life for those operated on, and reducing the incidence of pathological reactions to the functional state of the brain. For the past decade and a half, the Novosibirsk Research Institute of Traumatology and Orthopedics has been using neodymium laser radiation with a wavelength of 1.064 μm to remove cerebral meningiomas. This allows for a reduction in brain trauma, a reduction in the severity of focal and general cerebral symptoms in the early postoperative period, and an increase in the radicality of meningioma removal [5]. This is one possible solution to the above-mentioned problems. We emphasize that when examining the clinical manifestations in the study patients in the late

postoperative period, we took into account that the majority of these manifestations develop due to cerebral blood flow disturbances, as well as severe cicatricial and cystic degenerative processes in the surgical area [1, 4]. We have not encountered cases of similar studies and observations of patients in the late postoperative period, especially those operated on using a surgical laser. To fill this gap, we considered it appropriate to conduct an analysis of the functional state of the brain in such patients in the late period, based on the results of an objective instrumental examination. One of the available methods that allows us to compare the obtained data is the recording and study of electroencephalograms, as well as the study of cerebral blood flow using transcranial Doppler sonography. In this regard, the aim of the study was formulated - to evaluate the effectiveness of the developed laser technologies in the removal of cerebral meningiomas in patients in the late postoperative period by comparing cases of cerebral hemodynamic disorders, as well as manifestations of pathological changes obtained using EEG studies. Material and methods We analyzed the long-term results of surgical treatment (more than 5 years from the date of surgery) of 389 patients with basal (175 cases) and parasagittal (214 cases) meningiomas of the brain of complex localization and operated on at the Novosibirsk Research Institute of Traumatology and Orthopedics from 1995 to 2009. All of them were operated on using modern microsurgical techniques and, depending on the tumor removal technique, were divided into two groups. Patients in the comparison group were operated on using standard microsurgical methods (using magnifying optics, microsurgical techniques, bipolar coagulation, and an ultrasonic disintegrator-aspirator). In addition to standard meningioma removal methods, the study group used innovative laser technologies based on the neodymium laser at certain stages of resection. The groups were comparable in terms of gender, mean patient age, pathology, meningioma matrix location at the skull base, mean follow-up time, and the location of the meningioma along the SSS (Table 1).

Table 1. General characteristics of operated patients

Indicator	Basal meningiomas			PSM		
	Comparison group	Research group	Total	Comparison group	Research group	Total
Total number of patients, n	75	100	175	102	112	214
Age, years (M ± m)	61.6 ± 1.9	59.0 ± 1.2	62.9 ± 1.1	60.1 ± 2.4	62.8 ± 1.1	62.8 ± 1.1
Men, n (%)	17 (22.7)	24 (24.0)	41 (23.4)	25 (24.5)	18 (16.1)	43 (20.1)
Women, n (%)	58 (77.3)	76 (76.0)	134 (76.6)	77 (75.5)	94 (83.9)	171 (79.9)
Observation period after surgery, months (M ± m)	134 ± 9.4	113.4 ± 4.8	122.5 ± 5.0	134 ± 10.4	115.4 ± 3.7	130 ± 9.4

There were no significant differences in the tumor matrix localization between the groups either. Thus, there were 20 (17.9%) basal meningiomas in the anterior third of the basal cranial fossa in the study group and 17 (16.7%) in the comparison group, 62 (55.4%) and 58 (56.9%) in the middle third of the basal cranial fossa, respectively, and 30 (26.7%) and 27 (26.4%) in the posterior third of the basal cranial fossa, respectively. Basal meningioma matrix was diagnosed in the anterior cranial fossa in the study group in 31 (31%) and 16 (21.3%) patients in the comparison group, in the middle cranial fossa in 48 (48%) and 35 (46.7%) patients, respectively, and in the posterior cranial fossa in 21 (21%) and 24 (32%) patients, respectively. Among the removed basal meningiomas, typical neoplasms accounted for 82.14% in the study group, atypical – 14.29%, and anaplastic – 3.57%. In the comparison group, similar histological variants were diagnosed in 79.41, 17.65, and 2.94% of cases, respectively. The morphological structure of basal meningiomas in the study group was as follows: typical meningiomas accounted for 90%, atypical – 8%, and anaplastic – 2%; in the comparison group, the figures were 90.7, 8, and 1.3%, respectively. Technological methods for using a neodymium laser to remove parasagittal and basal meningiomas are described in detail by V.V. Stupak et al. [5]. In the late postoperative period, the functional state of the brain of all 389 operated patients was analyzed based on EEG parameters using a Neurofax encephalograph (Nihon Kohden, Japan). The frequency of pathological changes in the electrical activity of the brain was compared according to the classification of L.R. Zenkov [2]. The following manifestations of pathological changes in the EEG were analyzed: 1) diffuse changes (mild, moderate, severe), 2) focal changes, 3) the presence of epileptiform activity, 4) signs of dysfunction of the midline structures. Cerebral blood flow parameters were assessed based on transcranial Doppler sonography using a MultiDop-T DWL apparatus (Electronische Systeme GmbH, Germany); the linear systolic blood flow velocity in the middle cerebral artery (MCA) was studied on both sides. To determine the peripheral resistance of the vascular wall of the MCA in patients operated on for basal meningiomas and for an indirect assessment of intracranial pressure, the pulsatility index Pi was used. The age norm was taken as the data on the maximum systolic linear blood flow velocity in the MCA from 78.1 to 91.0 cm/s and $Pi = 0.86 \pm 0.14$ in the age group from 40 to 60 years [7]. Statistical processing of the study results was performed by calculating the arithmetic mean (M), the error of the arithmetic mean (m), and presented as $M \pm m$. Nominal data are presented as relative frequencies of the study objects (n, %). To assess the differences in quantitative data, the Mann-Whitney test was used, for nominal data - Fisher's exact test. The critical level of significance of the null statistical hypothesis (p) was taken equal to 0.05.

Results and discussion. The original technologies for cerebral meningiomas resection developed by us allow to achieve the highest possible degree of radicality of surgical interventions in the overwhelming majority of patients and decrease the number of patients with partial tumor removal. The maximum possible complete removal of basal meningiomas according to the D. Simpson scale was achieved in 89.8% of cases, partial resection was performed in 10.2% of patients. In the comparison group, total removal of the tumor node was performed in 63.75% of cases, partial - in 36.25%. In PSM, the use of laser, regardless of the degree of SSS invasion, in the overwhelming majority of patients (99%) achieved the maximum degree of meningioma removal. Along with this, the reduction of brain trauma, the severity of postoperative cerebral edema and vascular disorders leads to a decrease in postoperative mortality. In the group using the laser, it was 3.0%, in patients operated

on by traditional methods, it was equal to 5.0%. In the late postoperative period, when analyzing the EEG of all patients who had meningiomas in the anterior cranial fossa, moderately expressed diffuse changes in the bioelectrical activity of the cerebral cortex were revealed in almost the same proportion (Table 2).

Table 2. Frequency of pathological changes in EEG in the late postoperative period in patients operated with and without laser

The nature of pathological changes in EEG	Basal meningiomas, n (%)		PSM, n (%)	
	Comparison group	Research group	Comparison group	Research group
Diffuse changes	65 (86.7)	83 (83.0)	83 (81.4)	83 (74.1)
Focal changes	37 (49.3)	45 (45.0)	42 (41.2)	41 (36.6)
Dysfunction of midline structures	54 (72.0)	49 (49.0)	49 (48.0)	47 (42.0)
Presence of epileptiform activity	30 (40.0)	41 (41.0)	69 (62.0)	57* (56.0)

Note. Here and in Table 3: — the difference from the value of the corresponding indicator of the comparison group is statistically significant at $p < 0.05$.

In the study group, they were diagnosed in 27 patients (87.1%), and in the comparison group - in 14 (87.5%). Focal manifestations in the form of persistent slow waves are clearly expressed in the comparison group on the side of the initial tumor growth and were recorded in 11 (68.75%) patients. In the study group, this type of pathological EEG activity was presented to a lesser extent - in 16 (51.6%) operated patients and mainly represented single groups of slow waves. Thus, signs of mild dysfunction of midline structures and the presence of epileptiform activity are recorded somewhat less frequently in patients operated on using a laser, although the differences between the groups are not significant. In patients with the presence of a meningioma matrix in the middle cranial fossa, moderate diffuse irritative changes in the bioelectrical activity of the brain were also noted. In the study group, they were detected in 40 (83.3%) patients, in the comparison group - in 31 (88.6%) patients. Focal slow-wave activity and rare short generalized epileptiform discharges were recorded in equal proportions. Signs of dysfunction of the midline structures, reflected in the presence of low-amplitude single slow theta waves, were observed in 30 (62.5%) patients in the study group and in 29 (82.9%) patients in the comparison group. Similar data were obtained when assessing the nature of pathological changes in the electrical activity of the brain in patients operated on with meningioma matrix localization in the posterior cranial fossa. Moderate diffuse changes of an irritative nature were recorded in 16 (76%) patients in the study group and in 20 (83.3%) people in the comparison group. The presence of focal changes and epileptiform activity was observed in a small number of patients examined in both groups. Dysfunction of the midline structures was frequently recorded (in 18 patients (75%) operated on using standard technologies and in 7 (62.5%) in the study group). This means that in the long-term period, a clear trend towards better surgical treatment results using laser technologies is observed. When assessing the EEG in the late postoperative period in patients operated on for meningiomas of the anterior, middle, and posterior thirds of the SCD, mild to moderate diffuse changes

in the bioelectrical activity of the cerebral cortex were recorded in subjects whose meningiomas were removed using laser technologies. In the comparison group, diffuse changes were more often moderate in nature, with an emphasis on one of the cerebral hemispheres. In a small number of cases, focal changes were recorded in patients of both groups in approximately equal proportions; they were manifested by the presence of bilateral slow waves. Signs of dysfunction of the midline structures of the brain were also observed in almost equal proportions. In patients operated using a laser, slow theta waves were recorded locally in the parasagittal regions, less frequently delta waves without clear lateralization. In the comparison group, a clear lateralization of the brain region containing slow-wave theta activity was more frequently observed. Various manifestations of epileptiform activity were frequently detected in all patients operated on, regardless of the localization of the meningioma matrix relative to the extent of the SCD; however, they were more clearly expressed in the comparison group and represented short generalized epileptiform discharges. In patients who underwent laser resection of the meningioma matrix, epileptiform activity was observed significantly less frequently ($p = 0.02$) during the late postoperative period, despite the ongoing restorative therapy. This fact can be explained by the contactless and significantly less traumatic impact of surgical manipulations on the surrounding brain tissue during meningioma removal and the preservation of important venous outflow pathways. Other pathological changes were recorded somewhat more frequently in the comparison group, although the differences did not reach the level of statistical significance. In patients with skull base meningiomas who underwent neodymium laser surgery, EEG signs of midline dysfunction were significantly less frequent ($p = 0.003$) at late follow-up. This type of EEG abnormality is associated with pathological changes at the level of the basal structures. Therefore, the lower incidence of these abnormalities in patients in the study group is, we believe, also due to less surgical trauma to functionally significant areas of the brain during meningioma removal and less severe cerebral edema in the surgical area. This reduces the likelihood of worsening venous congestion and cerebral edema, and reduces the pathological impact on the functional state of the basal structures of the brain. A comparison of the values of systolic blood flow velocity in the middle cerebral artery in patients operated on for basal meningiomas in the late postoperative period revealed that in the study group on the side of the removed tumor it remained within the age norm and was higher than in the comparison group (Table 3). Other pathological changes were slightly more frequent in the comparison group, although the differences did not reach statistical significance. In patients with meningiomas located at the skull base and operated on using a neodymium laser, EEG signs of dysfunction of midline structures were significantly less frequent ($p = 0.003$) at late follow-up. This type of EEG abnormality is associated with pathological changes at the level of basal structures. Therefore, the lower incidence of these abnormalities in patients in the study group, we believe, is also due to less surgical trauma to functionally significant areas of the brain during meningioma removal and less severe cerebral edema in the surgical area. This reduces the likelihood of worsening venous congestion and cerebral edema, and reduces the pathological impact on the functional state of basal brain structures. A comparison of the values of systolic blood flow velocity in the middle cerebral artery in patients operated on for basal meningiomas in the late postoperative period revealed that in the study group on the side of the removed tumor it remained within the age norm and was higher than in the comparison group (Table 3). Other pathological changes were slightly more frequent in the comparison group, although the

differences did not reach statistical significance. In patients with meningiomas located at the skull base and operated on using a neodymium laser, EEG signs of dysfunction of midline structures were significantly less frequent ($p = 0.003$) at late follow-up. This type of EEG abnormality is associated with pathological changes at the level of basal structures. Therefore, the lower incidence of these abnormalities in patients in the study group, we believe, is also due to less surgical trauma to functionally significant areas of the brain during meningioma removal and less severe cerebral edema in the surgical area. This reduces the likelihood of worsening venous congestion and cerebral edema, and reduces the pathological impact on the functional state of basal brain structures. A comparison of the values of systolic blood flow velocity in the middle cerebral artery in patients operated on for basal meningiomas in the late postoperative period revealed that in the study group on the side of the removed tumor it remained within the age norm and was higher than in the comparison group (Table 3).

Table 3. Systolic blood flow velocity in the MCA and the Pi value in the late postoperative period in patients with basal meningiomas

Blood circulation indicator	Comparison group	Research group
Systolic blood flow velocity in the MCA on the homolateral side, cm/s	67.96 ± 1.18	$92.44 \pm 0.83^*$
Systolic blood flow velocity in the MCA on the contralateral side, cm/s	89.31 ± 0.72	90.63 ± 0.53
Pi in the MCA on the homolateral side	1.06 ± 0.03	$0.81 \pm 0.01^*$
Pi in the MCA on the contralateral side	1.04 ± 0.03	$0.79 \pm 0.01^*$

The observed decrease in systolic blood flow velocity in patients operated on using traditional technologies is extremely important and has prognostical significance. It may be the cause of local ischemia and persistent signs of local cerebral edema, which is confirmed by the study of the pulsatility index. When assessing systolic velocity in the MCA on the contralateral side, no statistically significant differences were found between the groups ($p = 0.304$). In patients operated on using traditional methods of basal meningioma resection, the pulsatility index in the late postoperative period was statistically significantly higher compared to the study group (see Table 3), which is most likely associated with an increase in peripheral resistance with an increase in intracranial pressure [1] and indicates the presence of clinical signs of intracranial hypertension syndrome in patients in the comparison group.

Conclusion. The results of the conducted studies confirm the effectiveness of the developed laser technologies, which eliminate unwanted thermal effects on the main arterial vessels of the brain during the resection of basal and parasagittal meningiomas. In patients with basal meningiomas operated without the use of a laser, systolic blood flow velocity in the MCA on the homolateral side in the late postoperative period was statistically significantly lower than in the study group. In patients with parasagittal meningiomas operated on, only a tendency toward a decrease in systolic blood flow velocity in the MCA was observed in the comparison group. In most cases, the pulsatility index in the late postoperative period after the removal of both basal and parasagittal meningiomas in patients

operated on using standard technologies significantly increased, which may confirm the presence of intracranial hypertension in these patients. This is also supported by the results of studies of the functional state of the brain in patients undergoing laser surgery, who show a significant tendency toward fewer pathological changes in EEG activity in the late postoperative period. Significant differences were found between the groups in the frequency of signs of dysfunction of midline structures in patients with basal meningiomas and in the presence of foci of epileptiform activity in patients with SCI.

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