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Alternative middle-flow extracranial-intracranial cerebral bypass using distal branches of the external carotid artery in patients with complex cerebral aneurysms (clinical cases and literature review)

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Background. The treatment of complex cerebral aneurysms is still remained the great challenge for neurosurgeons. There is a large choice of intravascular techniques for excluding the complex cerebral aneurysms from the blood flow: endovascular embolization with microcoils, usage of flow-diverting stents, balloon angioplasty and stenting of extra- and intracranial segments of the main cerebral arteries. At the same time, the microsurgical treatment of cerebral aneurysms has not lost its relevance and remains the most radical method of treatment. However, simple clipping or reconstruction of complex aneurysm wall is not always possible. In such cases, trapping of parent artery and revascularization of the required blood supply territory are used.

Aim. To present the two clinical cases of patients with complex intracranial aneurysms without the possibility of endovascular treatment, who underwent parent artery trapping and alternative middle flow extracranial-intracranial (EC–IC) bypass as well as to conduct the literature review concerning the key aspects of this topic.

Clinical cases. This article presents two patients operated on for complex intracranial aneurysms. The first patient had a complex fusiform-saccular aneurysm of the left middle cerebral artery (MCA) with a frontal M2 segment of the left MCA extending from the fusiform dome; the second patient had a giant saccular aneurysm of the supraclinoid segment of the left internal carotid artery (ICA) and a complete posterior trifurcation on the left. Endovascular treatment was considered as impossible. The trapping of the parent artery and performing of middle-flow EC–IC bypass using the distal branches of the external carotid artery (ECA) were conducted. Intraoperative frameless neuronavigation was used.

Conclusion. The use of terminal branches of the ECA (maxillary artery and proximal part of superficial temporal artery) expands the possibilities of cerebral revascularization performing in cases where low- or middle-flow EC–IC bypasses are required. The relatively rare use of these arteries in practice and few publications about these types of bypasses require careful selection of patients with preoperative assessment of the brachiocephalic arteries and hemodynamic parameters.

Keywords: complex aneurysms, intracranial aneurysms, surgical cerebral revascularization, extracranial-intracranial bypass, external carotid artery, frameless neuronavigation

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BACKGROUND

The treatment of complex cerebral aneurysms is still remained the great challenge for neurosurgeons. The development of endovascular surgery has significantly expanded the number of treated patients with previously supposed unclippable cerebral aneurysms. Nowadays the large choice of intravascular techniques for excluding the complex cerebral aneurysms from the blood flow are available (endovascular embolization with microcoils, usage of flow-diverting stents, balloon angioplasty and stenting of extra- and intracranial segments of the main cerebral arteries). Meanwhile, the microsurgical treatment of cerebral aneurysms remains the most radical method of cerebral aneurysm treatment [1, 2].

On the other hand, the simple clipping or reconstruction of complex aneurysm wall is not always possible. In such cases, trapping of parent artery and revascularization of the required blood supply territory are used. The most common types of flow replacement bypass are routine high-flow extra-intracranial (EC–IC) bypass using the external carotid artery (ECA) as a donor artery, as well as low-flow EC–IC bypass using branches of the superficial temporal artery (STA) (including double-barrel bypass, when both STA branches are used simultaneously) [3–6].

In some cases, when EC–IC bypass is required, the use of STA branches is not possible due to their hypoplasia, insufficient diameter or low functionality (blood flow volume is significantly less than in the recipient artery) or blood flow in STA branches may not be sufficient to replace the required blood volume. In such cases, it is permissible to perform the so called "alternative middle-flow" types of bypass using "auxiliary" donor arteries: the main trunk of the STA, the maxillary artery (MA), and an interposition vascular graft.

The aim of this publication is to present the two patients with complex intracranial aneurysms without the possibility of endovascular treatment, who underwent parent artery trapping and alternative middle-flow EC–IC bypass as well as to review the literature data on the key aspects of this topic.

CLINICAL CASE 1

***Male patient M.**, 56 years old, applied (2023) to the scientific-advisory department of the Research Center of Neurology (RCN) complaining on periodically occurring attacks of headache, transient weakness in the right arm and leg. From the anamnesis it is known that more than 20 years ago during the examination a small aneurysm of the bifurcation of the M1 segment of the left middle cerebral artery (MCA) was detected, which did not require surgical treatment that time.*

Repeated visit was made in 2023, when the above-mentioned complaints appeared. Patient suffered from arterial hypertension. Upon examination, the general condition was satisfactory. Somatic status was unremarkable. There was transient extrapyramidal insufficiency in neurological status.

***Diagnosis.** According to CT angiography of the intracranial arteries, a large aneurysm of the M1 bifurcation segment of the left MCA with a fusiform-saccular structure was detected. The fusiform part of the aneurysm was 21 mm in diameter and extended to the M2 segment (frontal branch) of the left MCA. The saccular component was localized in bifurcation of the M1 segment of the left MCA, the size of the dome and neck was 6 and 7.1 mm, respectively (Fig. 1).*

The digital cerebral angiography confirmed the presence of a complex fusiform-saccular aneurysm of the left MCA with frontal M2 segment of the left MCA arising from the fusiform aneurysmal dome (Fig. 2).

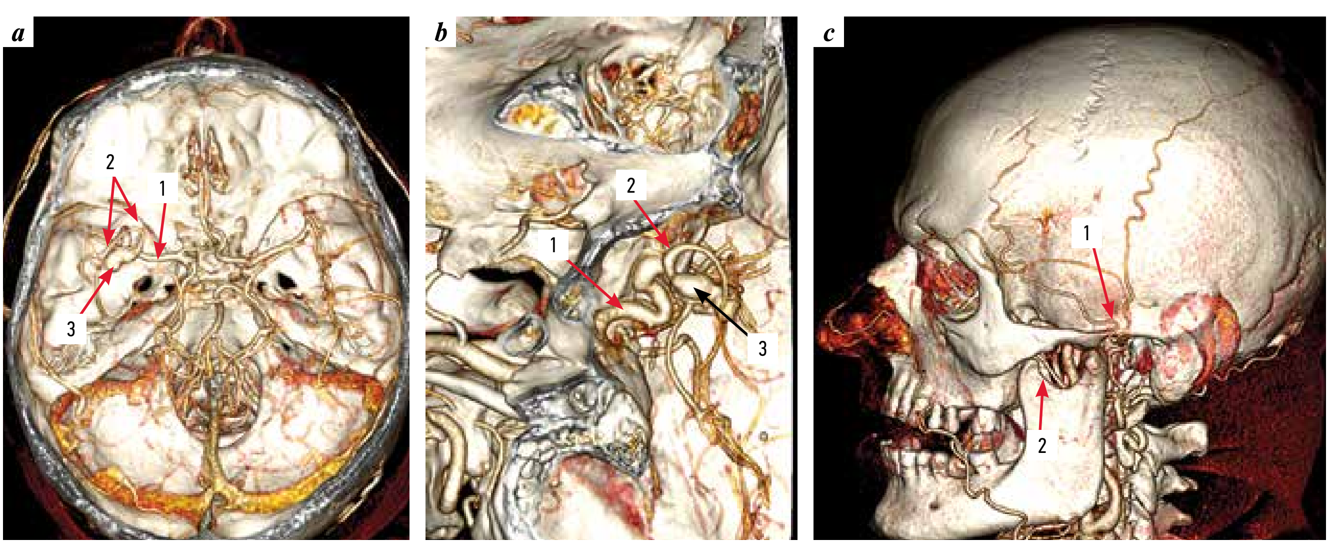

Fig. 1. *CT angiography before surgery, 3D reconstruction: a – intracranial arteries, axial view: 1 – M1 segment of the left middle cerebral artery (MCA), 2 – M2 segments of the left MCA, 3 – saccular part of the aneurysm of the left MCA bifurcation; b – intracranial arteries, sagittal view: 1 – left internal carotid artery, 2 – M2 segment (frontal branch) of the left MCA, 3 – fusiform part of the aneurysm of the left MCA bifurcation; c – extracranial arteries: 1 – trunk of the superficial temporal artery, 2 – maxillary artery*

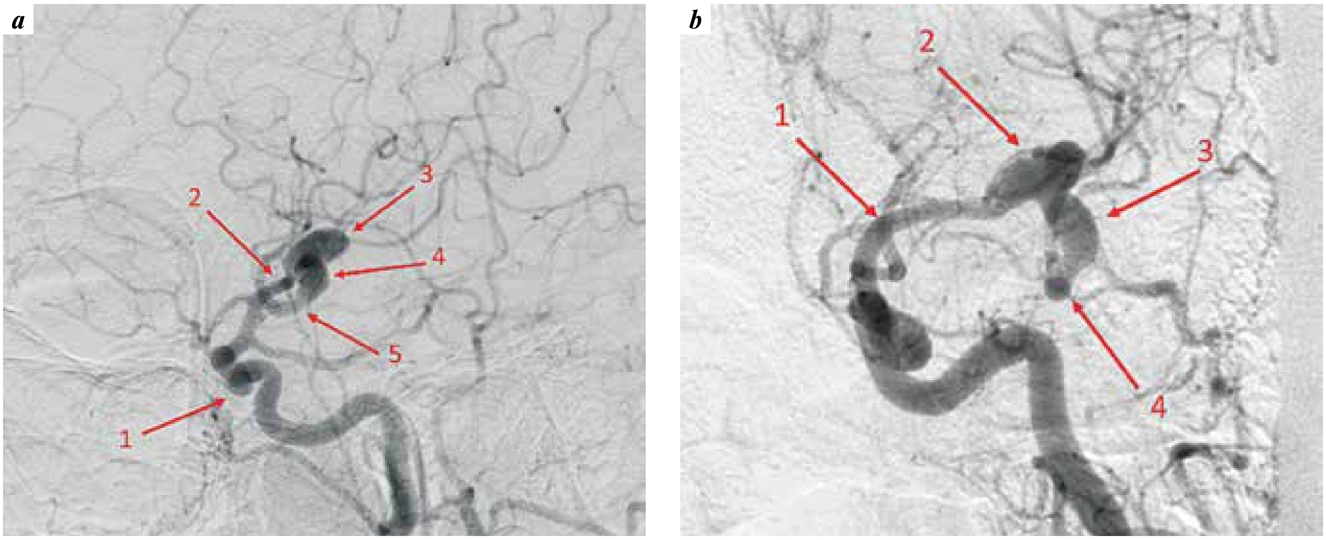

Fig. 2. *Digital cerebral angiography: a – sagittal view: 1 – left internal carotid artery, 2 – M1 segment of the left middle cerebral artery (MCA), 3 – saccular part of the aneurysm of the left MCA bifurcation, 4 – fusiform part of the aneurysm of the left MCA bifurcation, 5 – M2 segment of the MCA; b – coronal view: 1 – M1 segment of the left MCA, 2 – saccular part of the aneurysm of the left MCA bifurcation, 3 – fusiform part of the aneurysm of the left MCA bifurcation, 4 – frontal branch of the M2 segment of the left MCA*

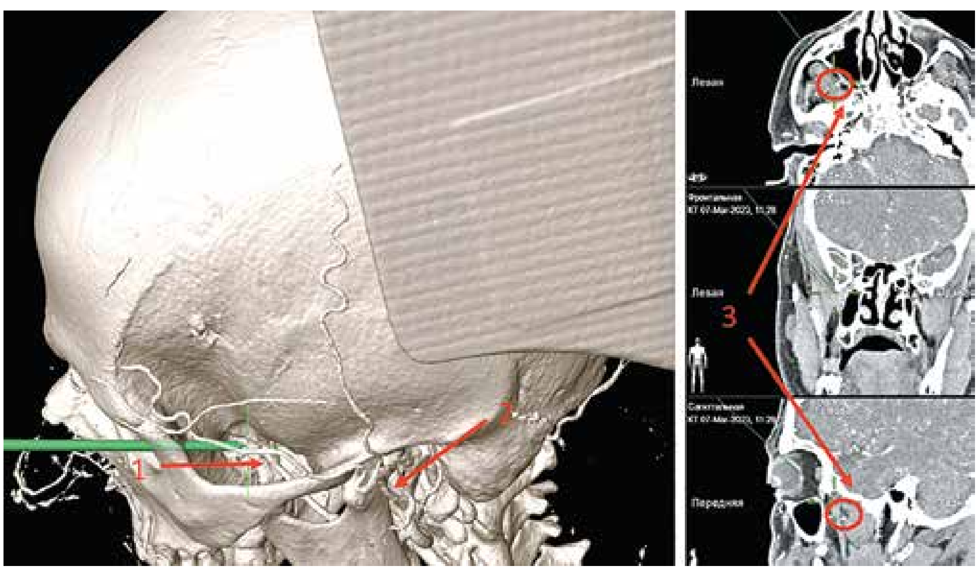

Fig. 3. *Intraoperative frameless neuronavigation: 1 – maxillary artery (MA); 2 – trunk of the superficial temporal artery; 3 – MA*

Taking into account the significant increase of aneurysmal sizes and symptoms onset, the surgical treatment was recommended. The patient was admitted to neurosurgical department of the RCN for scheduled surgical treatment.

The planning and performing of operation*. Given the fusiform-saccular nature of the aneurysm and the impossibility of performing endovascular and reconstructive intervention, a decision was made to conduct the revascularization procedure followed by the trapping of the aneurysmal fusiform part. The reanastomosis of the frontal M2 segment of the left MCA was assumed. The left MA and the left STA trunk were considered as donor arteries, and the radial artery (RA) was supposed as a vascular graft.*

Under general anesthesia, the patient was placed on the operating table on his back, the head was rigidly fixed in a three-point frame with a 45° turn to the right. Preoperative marking of possible donor and recipient arteries was performed using frameless neuronavigation (Fig. 3).

Due to the low level of localization of the MA (see Fig. 3) and the technical inconvenience of its use, it was decided to use the STA trunk (see Fig. 1c). During the operation, intraoperative neurophysiological monitoring (IONM) was performed to record the motor evoked potential (MEP) from the muscles of the right upper and lower extremities in response to transcranial electrical stimulation of the cerebral cortex.

The soft tissue incision was made in the left frontotemporal region and the STA was isolated before it divided into terminal branches. The pterional craniotomy was performed, the dura mater was opened in an arcuate manner and turned toward to the base of the skull. Dissection of the left Sylvin fissure was *performed with step-by-step dissection and visualization of the left internal carotid artery (ICA), the M1 segment of the left MCA, the aneurysm and the M2 segments of the left MCA. The aneurysm was a polygonal irregular figure, from the dome of which the frontal M2 segment of the left MCA arose.*

The second team of surgeons harvested the RA, flushed the graft with heparin solution, and performed the water distension technique. After preparing the ends of the donor artery and the graft, a proximal "end-to-end" anastomosis was performed between the STA and the RA using the double fish-mouth technique. Then, proximal trapping of the fusiform aneurysm was performed with preserving the temporal M2 segment. After distal trapping of the aneurysm, the frontal branch of the M2 segment of the MCA was cut off within the unchanged arterial wall (Fig. 4).

The next stage was "end-to-end" reanastomosis between the distal end of the bypass graft (from the RA) and the M2 segment of the MCA using the "double fish mouth" technique. When the blood flow started, a distinct pulsation along the graft was noted. The M2 segment of the MCA was cross-clamped for 32 min. Intraoperative fluorescein angiography showed no blood flow in the aneurysm, as well as patency of the bypass graft, and filling of the frontal M2 segment from the STA blood supply territory (Fig. 5). The linear blood flow velocity using contact Doppler ultrasonography along the M2 segment of the MCA was 25 cm/s, along the vascular graft – 20 cm/s. MEP was unchanged. Final hemostasis was performed using local hemostatic material Surgicel fibrillar. Layer-by-layer wound suturing was performed.

***Postoperative period** was without complications and patient had no worsening of neurological symptoms. The control CT angiogram showed no signs of aneurysm filling, the bypass was patent, the M2 segment (frontal branch) is filled from the STA blood supply territory (Fig. 6). The patient was activated on the 3rd day after surgery (Fig. 7), discharged on the 8th day, the wound healed by primary intention. The follow-up was during 7 months – cerebral and focal*

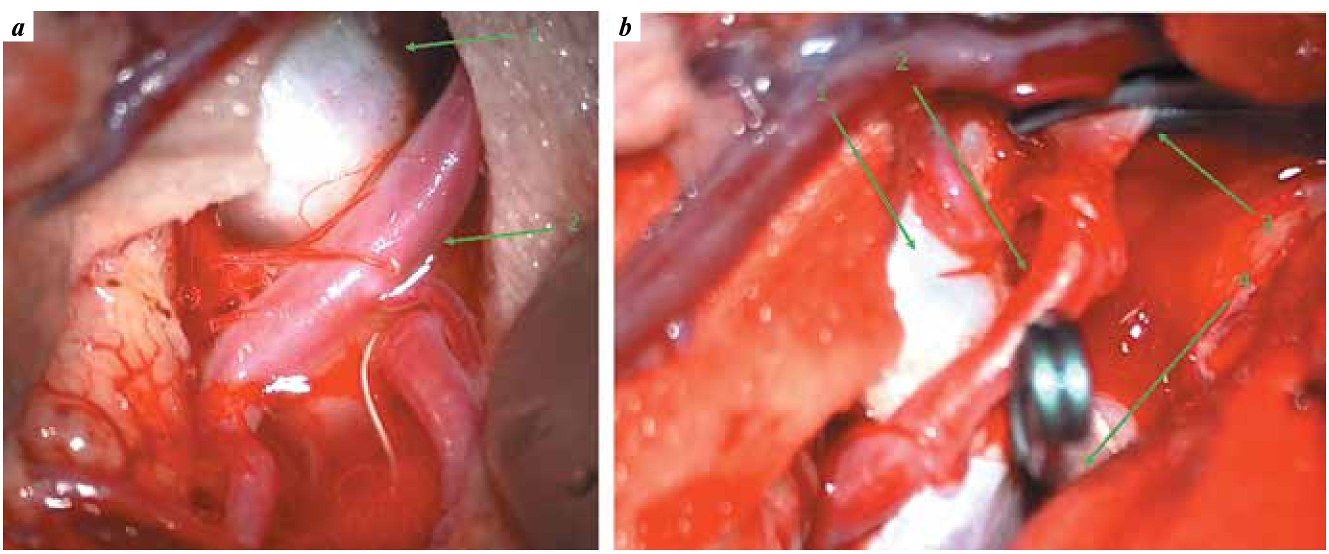

Fig. 4. *Intraoperative images: before the intervention (a) and during trapping (b): 1 – aneurysm; 2 – M2 segment of the middle cerebral artery (MCA); 3 – distal trapping of the MCA; 4 – proximal trapping of the MCA*

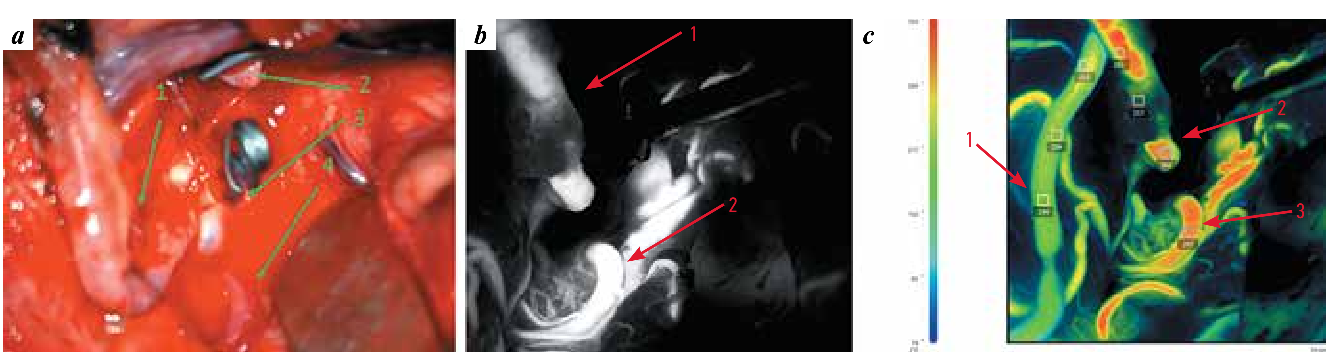

Fig. 5. *Intraoperative ICG angiography. a – intraoperative view after placement of aneurysmal clips: 1 – anastomosis between the superficial temporal artery (STA) trunk and the M2 segment of the middle cerebral artery (MCA), 2 – distal trapping of the MCA, 3 – proximal trapping of the MCA, 4 – M2 segment of the MCA; b – intraoperative angiography (ICG): 1 – anastomosis between the STA trunk and the M2 segment of the MCA, 2 – M2 segment of the MCA; c – blood flow velocity calculation (ICG FLOW): 1 – STA graft; 2 – anastomosis between the STA trunk and the M2 segment of the MCA; 3 – M2 segment of the MCA*

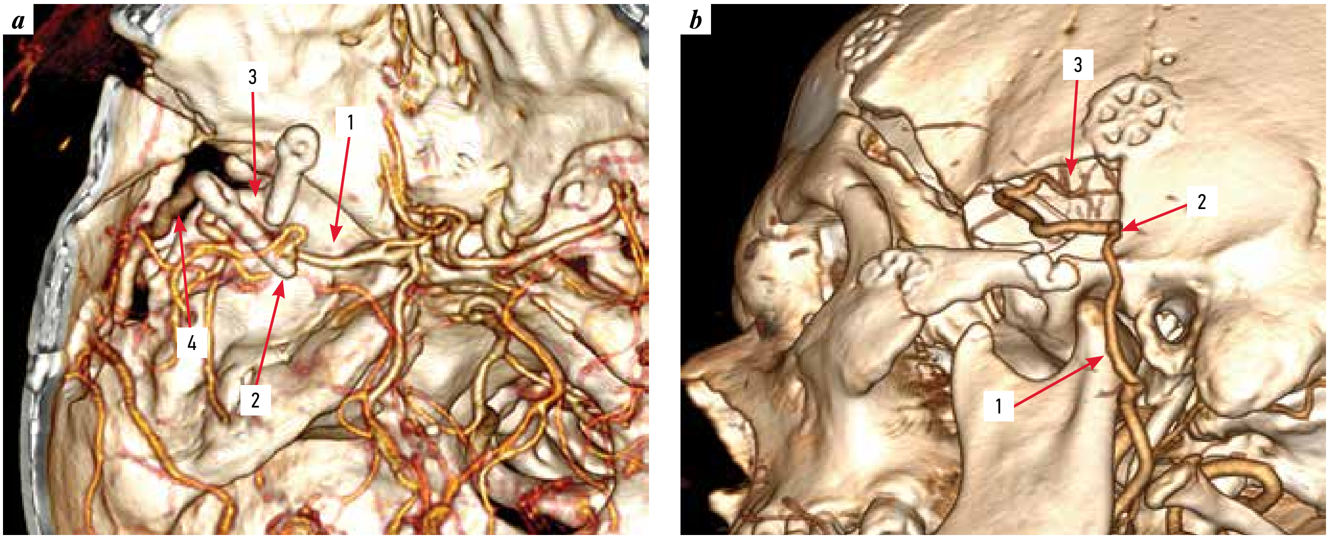

Fig. 6. *CT angiography on the 1st postoperative day, 3D reconstruction: a – intracranial arteries, the aneurysm is totally excluded from the blood flow: 1 – M1 segment of the left middle cerebral artery (MCA), 2 – proximal aneurysm trapping clip, 3 – distal aneurysm trapping clip, 4 – radial artery (RA) graft; b – extracranial arteries: 1 – superficial temporal artery, 2 – RA graft, 3 – M2 segment of the left MCA*

Fig. 7. *The patient was activated on the 3rd day after surgical treatment*

neurological symptoms regressed, the patient returned to his previous work.

CLINICAL CASE 2

Male patient K., *50 years old, began to notice the repeated attacks of headache and visual impairment for several months. He was consulted by an ophthalmologist, and right-sided upper quadrant hemianopsia was detected.*

Diagnosis. *CT angiography of the brain revealed a giant saccular aneurysm of the supraclinoid segment of the left ICA, measuring 26 × 17 mm, with a complete ICA posterior trifurcation on the left (Fig. 8).*

The patient was admitted to the neurosurgical department of RCN. Upon admission, the patient's condition was satisfactory, complaints were the same. Right-sided hemianopsia was confirmed in the neurological status.

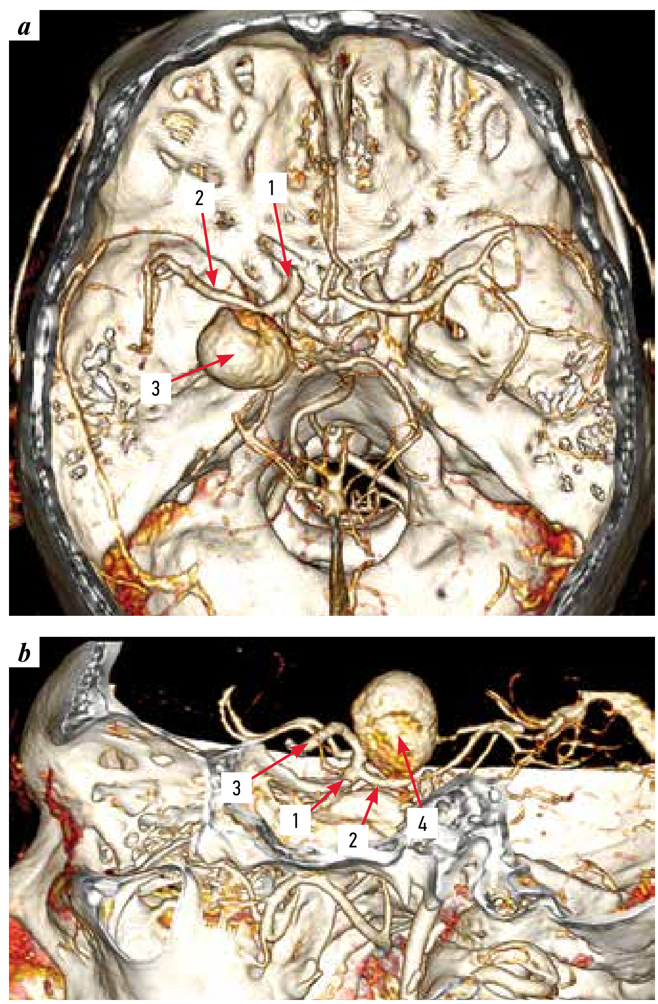

Fig. 8. *CT angiography before surgery, 3D reconstruction: a – incomplete circle of Willis, ICA posterior trifurcation on the left: 1 – left internal carotid artery (ICA), 2 – left middle cerebral artery (MCA), 3 – aneurysm dome; b – extra-intracranial arteries, sagittal view: 1 – left ICA, 2 – left PCA, 3 – left MCA, 4 – aneurysm body*

Fig. 9. *Intraoperative frameless neuronavigation: 1 – maxillary artery (MA) on 3D reconstruction; 2 – MA on MPR reconstruction*

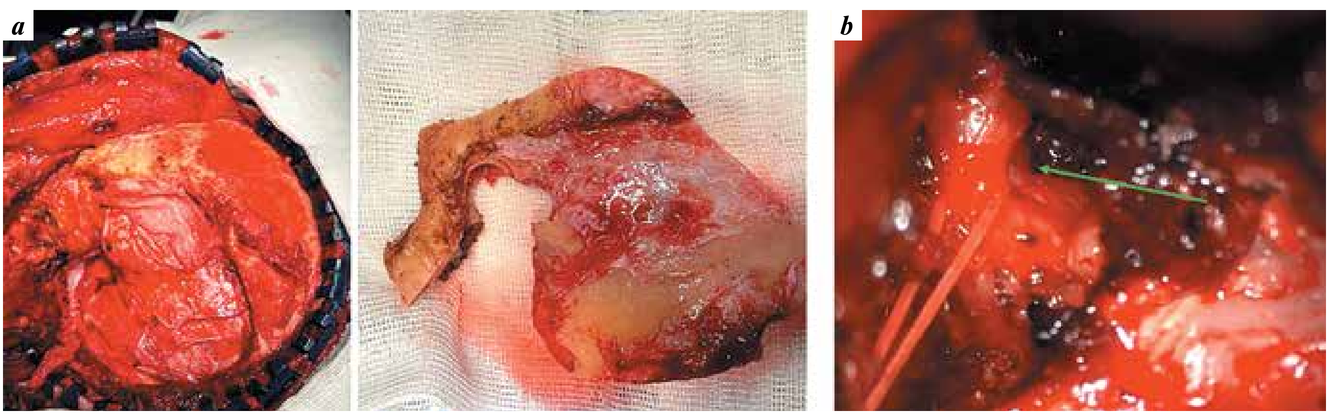

Fig. 10. *Intraoperative images: a – orbitozygomatic craniotomy; b – the maxillary artery (indicated by the green arrow) in the infratemporal fossa is isolated and taken on ligatures*

Planning and performing the operation. *Given the size and location of the aneurysm, its mass effect, and the development of focal neurological symptoms, endovascular treatment was associated with a high risk of complications. A decision was made to perform trapping of the left ICA distal to the anterior choroid artery with revascularization of the M2 segment of the left MCA from the MA using the RA as a graft. During the operation, under general anesthesia, IONM was used with registration of MEP from the muscles of the right upper and lower extremities in response to transcranial electrical stimulation of the cerebral cortex. The patient was positioned supine, the head was rigidly fixed in a three-point frame with a 45° head rotation to the right. Using frameless neuronavigation, the location of the MA was determined, the localization of the artery was recognized as accessible (Fig. 9).*

The soft tissue incision was made in the left frontotemporal region, orbitozygomatic craniotomy was performed, the maxillary artery was isolated and taken on ligatures (Fig. 10).

After craniotomy, dissection of the Sylvian fissure was performed with step-by-step dissection and visualization of the left ICA, hypertrophied PCoA, MCA and aneurysm dome. With temporary proximal clipping of the ICA for 10 min, the aneurysm was dissected with the visualization of multiple perforators arising from the dome and the neck part of the aneurysm, including the anterior choroid artery (Fig. 11). While performing the temporary ICA clipping, the marked MEP decrease from the right extremities was noted.

After preparation of the donor and recipient arteries ends, the proximal "end-to-end" anastomosis was performed between the MA and the RA graft using the "double fish mouth" technique. The next step was to perform an "end-to-side" anastomosis between the distal end of the bypass graft and the M3 segment of the MCA. The blood flow started, and a distinct pulsation of the bypass was observed. The time of the M3 segment of the left MCA cross-clamping was 38 min. Then, the trapping of the left ICA was performed while maintaining retrograde blood flow through the anterior choroid artery. The

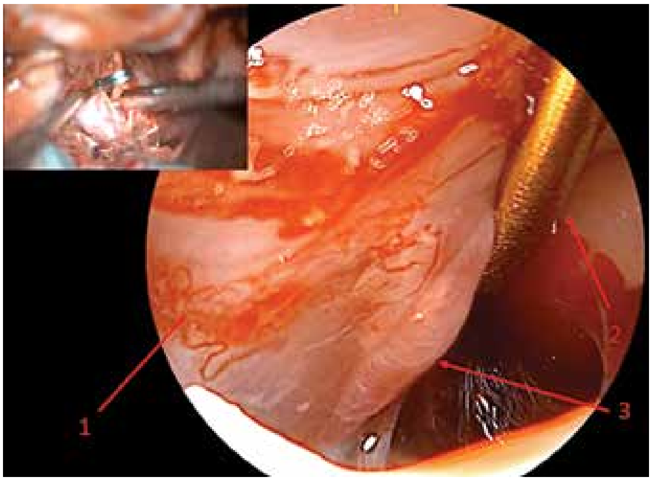

Fig. 11. *Videoendoscopic control (intraoperative image): 1 – internal carotid artery; 2 – aneurysmal titanic clip; 3 – anterior choroid artery. The radial artery was harvested, the graft was flushed with heparin solution, and the water distension technique was performed*

blood supply territories of the left MCA and the anterior choroid artery were filled through the RA graft as well as the blood flow in the aneurysm slowed down and acquired a retrograde, turbulent character according to the intraoperative fluorescein angiography data (Fig. 12).

After the blood flow started, partial restoration of the amplitude of the MEP from the muscles of the right limbs was noted. The bone flaps were fixed; the graft was placed under the zygomatic bone. Layer-by-layer suturing of the wound was performed.

Postoperative period. *The patient was in the anesthesiology and intensive care unit. The sensor and motor aphasia as well as right-sided hemiparesis up to 1 score in the arm, up to 4 scores in the leg, and dysfunction of the left oculomotor nerve were reveled on 1st postoperative day. Postoperative brain CT scan, CT angiography, and CT perfusion were performed. The aneurysm was thrombosed, brain retraction injuries in the area of the surgical intervention up to 10 cm^3 are determined, the bypass was patent and supplied the left MCA and left anterior choroid artery territories (Fig. 13).*

Thanks to rehabilitation measures, positive dynamics was noted in the patient's condition in 30 days after surgery, including the regression of speech and motor impairments (Fig. 14).

DISCUSSION AND LITERATURE REVIEW

1. Formation of bypasses: usage of the superficial temporal artery trunk

The use of the STA trunk as a donor artery can be divided into two types:

1) use of the ipsilateral STA trunk [7–12];
2) use of the trunk and branches of the contralateral STA to form a "bonnet" (from the French word for cap) and "hemi-bonnet" (half-cap) bypass [13–25].

1.1. The usage of the ipsilateral superficial temporal artery trunk. The trunk of the STA can be used as a donor artery, with the RA becoming the vascular graft for the middle-flow bypass. This type of bypass is rarely performed [7]. Such operations are advisable in cases where the forming of routine low-flow EC–IC bypass is impossible due to insufficient diameter of the STA branches, severe atherosclerotic changes, and their dissection. The authors noted that during postoperative period after performing this type of bypasses, the hemodynamic parameters are similar to those in the case of high-flow EC–IC bypass, which is explained by the dynamics of blood flow according to Poiseuille's laws [11, 12].

1.2. The formation of a bonnet-type bypass. The contralateral STA is used as a donor. This technique is most often used for occlusion of the ipsilateral common carotid arteries or ECA, or when it is necessary to deliberately exclude these vessels from the blood flow [14, 16, 22]. The original technique for performing this type of bypass involves the formation of two anastomoses. The first anastomosis is formed between the contralateral STA and the proximal end of the graft. Then, a bone tunnel is created in the cranial vault, into which the bypass is placed. The

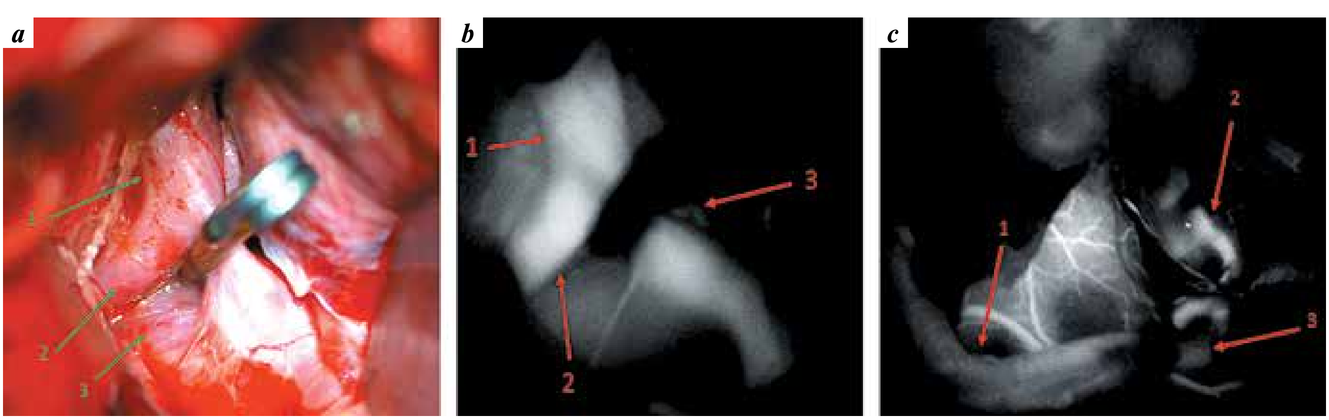

Fig. 12. *Intraoperative images: a – trapping of the internal carotid artery (ICA) was performed before to the origin of the anterior choroid artery: 1 – ICA, 2 – posterior communicating artery, 3 – aneurysm; b – intraoperative ICG angiography: 1 – ICA; 2 – posterior communicating artery; 3 – anterior choroid artery; c – intraoperative ICG angiography: 1 – graft from the radial artery; 2 – ICA; 3 – middle cerebral artery*

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Russian Journal of Neurosurgery
2 ТОМ 27 Vol. 27 2025

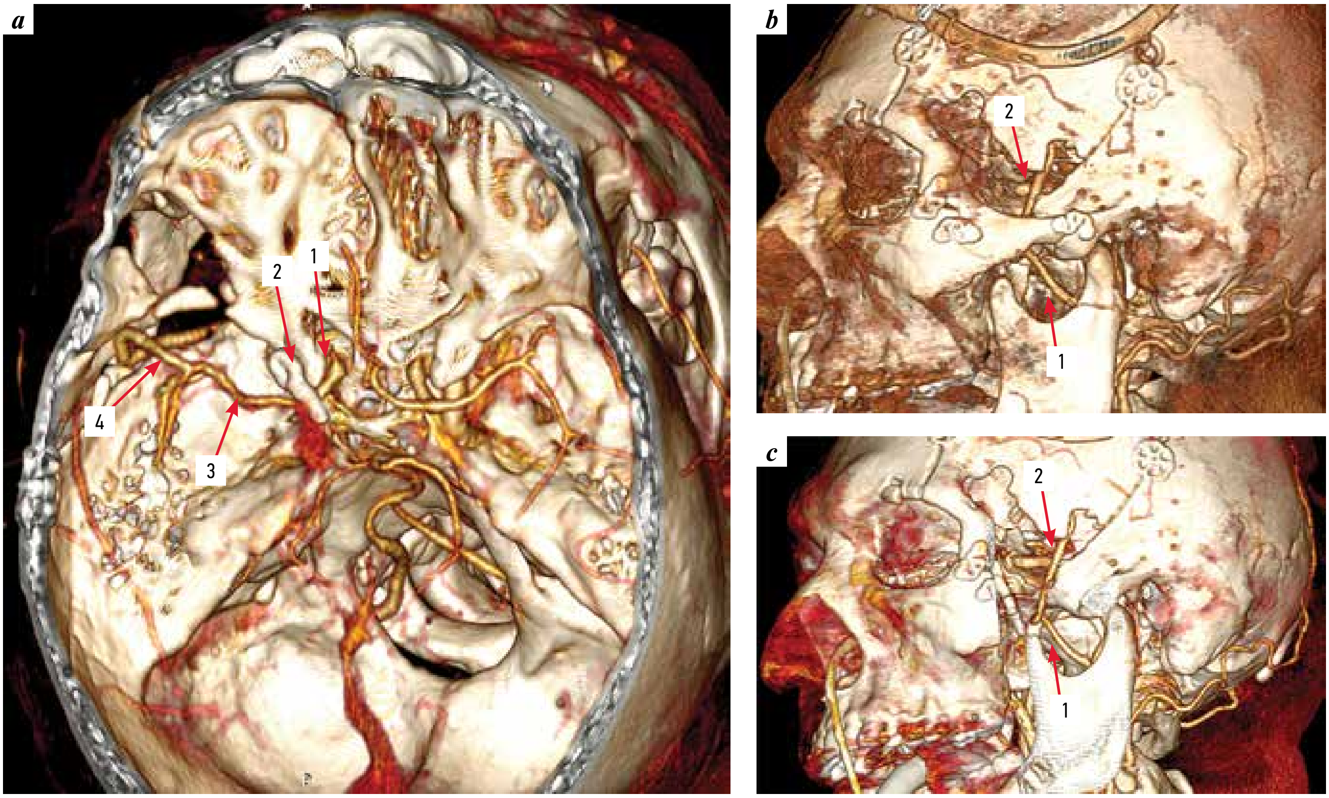

Fig. 13. *CT angiography (1st postoperative day), 3D reconstruction: a – the aneurysm was excluded from the blood flow, the left middle cerebral artery (MCA) territory was filled via the radial artery (RA) bypass: 1 – left internal carotid artery (ICA), 2 – trapping of the left ICA, 3 – left MCA, 4 – RA graft; b – extracranial arteries: 1 – maxillary artery (MA), 2 – RA graft; c – the zygomatic bone is virtually removed: 1 – MA, 2 – RA graft*

final stage is the formation of the second anastomosis between the distal end of the graft and a branch of the MCA (M2, M3, or M4 segments).

Modifications of the bonnet technique. In cases where an interposition graft is required between the STA and the arteries located in the interhemispheric fissure, a modification of the bonnet technique is possible [23–25]. The hemi-bonnet technique is applicable on the case of ACA aneurysms, when a distal anastomosis is formed with the pericallosal arteries. The formation of a distal anastomosis using this technique is usually performed using "end-to-end" or "end-to-side" technique.

In another modification of the bonnet bypass technique, the STA is used if there is sufficient retrograde blood flow from the contralateral STA through a developed network of collaterals. In this case, the STA on the affected side is used as a donor artery. At the first stage, retrograde blood flow is assessed during cerebral subtraction digital angiography, infrared angiography, intraoperative flowmetry and Dopplerography. Then, the ipsilateral STA is dissected, cut proximally to its bifurcation followed by the anastomosis performing with a branch of the MCA.

Fig. 14. *The patient was activated and nowadays he fully takes care of himself (7 months after surgical treatment)*

2. Usage of the maxillary artery

This technique was first proposed as an alternative to routine high-flow EC–IC bypass by S. Abdulrauf et al. (2011). The author highlighted two advantages such as no need to form a colotomy and dissect the carotid artery as well as the shortest length of the graft required to perform bypass [26].

2.1. Intracranial dissection of the maxillary artery. Routinely, the access to the maxillary artery is performed intracranially by drilling out the bottom of the middle cranial fossa, after which the maxillary artery is anastomosed with the MCA using an interposition graft [27]. Later, the usage of the maxillary artery was applied for revascularization of the vertebrobasilar system [28, 29]. For this purpose, after craniotomy and opening of the dura mater, the lateral triangle of the middle cranial fossa is identified between the sphenosquamosal and petrosquamous sutures lateral to the spinous and oval foramina. Access to the infratemporal fossa via this triangle serves as the key to dissect the maxillary artery.

2.2. Extracranial dissection of the maxillary artery. Another option is the extracranial access and dissection of the maxillary artery in the infratemporal fossa. The peculiarity of this manipulation is the dissection of the maxillary artery via the orbitozygomatic (or transzygomatic) approach and skeletization of the temporal and lateral pterygoid muscles in the infratemporal fossa.

Careful preoperative planning and the usage of neuronavigation are the keys to successful verification of the maxillary artery.

Anatomical comparison of two options for access to the maxillary artery – extracranial (through the infratemporal fossa) and intracranial (through the middle temporal fossa) – showed that the advantages of the first are associated with simpler dissection of the artery and the absence of the need to drill the bottom of the middle cranial fossa [30].

In 2020, I. Peto et al. described an alternative technique for extracranial dissection of the maxillary artery in the region of the pterygomaxillary fissure, in the projection of which the maxillary artery passes. Dissection of the temporal muscle is performed, followed by zygomatic osteotomy. Then, after palpation identification of the posterior wall of the maxilla, it is necessary to dissect caudally until the pterygomaxillary fissure is detected, and then identify the maxillary artery [31]. These methods have some disadvantages associated with the complexity of searching and dissection the maxillary artery as well as the technical complexity of anastomosing the arteries and incomplete use of the resource of the volumetric blood flow of the maxillary artery (due to the division of blood flow during the formation of an end-to-side anastomosis).

In our paper [32] we proposed a method for dissecting the orifice of the maxillary artery from the preauricular approach, which provides the following advantages (in contrast to the other methods mentioned above): complete redirection of blood flow from the ECA by means of "end-to-end" anastomosis of the arteries; average graft length (12–14 cm); formation of a proximal anastomosis at a shallow depth comparable to the depth of the surgical field when anastomosing the arteries in the area of the bifurcation of the common carotid artery.

3. Intraoperative neurophysiological neuromonitoring

One of the main factors affecting the treatment outcomes is cerebral ischemia caused by temporary clipping during cerebral aneurysm surgery. One of the methods of intraoperative control of brain tissue perfusion is IONM. In 2021, F. Zhang et al. showed that electrophysiological monitoring during cerebral aneurysm clipping surgery contributes to a favorable prognosis even in case of postoperative cerebral ischemia development. It was found that a surgeon's rapid response to changes in electrophysiological parameters can prevent the development of neurological disorders caused by cerebral ischemia [33].

CONCLUSION

The usage of the terminal branches of the external carotid artery (maxillary artery and proximal part of superficial temporal artery) expands the possibilities of neurosurgeons in performing revascularization cerebral procedures in cases where low- and middle-flow extracranial-intracranial bypass is required. Despite the practical value, the relatively rare frequency of the maxillary artery and trunk of the superficial temporal artery usage in practice and the limited representation of these types of bypass in the literature require careful selection of patients with preoperative assessment of the brachiocephalic arteries and hemodynamic parameters.

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