Case Report

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Prediction of Resthenosis After Carotid Endarterectomy by the Method of Computer Simulation

A.N. Kazantsev[1] ✉, R.A. Vinogradov[2], Yu.N. Zakharov[3], V.G. Borisov[3], M.A. Chernyavsky[4], V.N. Kravchuk[5, 6], D.V. Shmatov[7], K.P. Chernykh[1], A.A. Sorokin[7], G.Sh. Baghdavadze[6], S.V. Artyukhov[1], G.G. Khubulava[5, 8]

Department of Surgery No. 3
[1] St. Petersburg City Alexandrovskaya Hospital
4 Solidarnosti St., St. Petersburg, 193312, Russian Federation
[2] S.V. Ochapovsky Research Institute and Regional Clinical Hospital No. 1 of the Ministry of Health of Russian Federation
167 1 Maya St., Krasnodar, 350086, Russian Federation
[3] Kemerovo State Medical University of the Ministry of Health of the Russian Federation
22a Voroshilova St., Kemerovo, 650056, Russian Federation
[4] V.A. Almazov National Medical Research Center of the Ministry of Health of Russian Federation
2 Akkuratova St., St. Petersburg, 197341, Russian Federation
[5] S.M. Kirov Military Medical Academy of the Ministry of Defense of the Russian Federation
6 Akademika Lebedeva St., St. Petersburg, 194044, Russian Federation
[6] I.I. Mechnikov North-Western State Medical University
41 Kirochnaya St., St. Petersburg, 191015, Russian Federation
[7] St. Petersburg State University, N.I. Pirogov Clinic of High Medical Technologies
7/9 Universitetskaya nab., St. Petersburg, 199034, Russian Federation
[8] I.P. Pavlov First St. Petersburg State Medical University of the Ministry of Health of the Russian Federation
6-8 Lva Tolstogo, St. Petersburg, 197022, Russian Federation

✉ **Contacts:** Anton N. Kazantsev, Cardiovascular Surgeon, Department of Surgery № 3, Aleksandrovskaya City Hospital. Email: dr.antonio.kazantsev@mail.ru

ABSTRACT The article describes a computer modeling technique that allows predicting the development of restenosis of the internal carotid artery after carotid endarterectomy (CEE). A clinical case has been demonstrated that proves the effectiveness of the developed method. It is indicated that for the correct formation of the geometric model, data from multispiral computed tomography with angiography of the patient after CEE with a layer thickness of 0.6 mm and a current of 355 mA are required. To build a flow model, data of color duplex scanning in three sections are required: 1. In the proximal section of the common carotid artery (3 cm proximal to the bifurcation); 2. In the section of the external carotid artery, 2 cm distal to the carotid sinus; 3. In the section of the internal carotid artery, 2 cm distal to the carotid sinus. The result of computer calculations using specialized software (Sim Vascular, Python, Open Foam) is a mathematical model of blood flow in a vessel. It is an array of calculated data describing the speed and other characteristics of the flow at each point of the artery. Based on the analysis of RRT and TAWSS indicators, a computer model of bifurcation is formed, which makes it possible to predict areas of increased risk of restenosis development. Thus, the developed technique is able to identify a cohort of patients after CEE, subjected to a high probability of loss of the vessel lumen. Such an opportunity will provide a more precise supervision of these patients in the postoperative period with the aim of early diagnosis of restenosis and timely prevention of the development of adverse cardiovascular events.

Keywords: carotid endarterectomy; classic carotid endarterectomy; eversion carotid endarterectomy; patch; restenosis; computer modelling

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Affiliations

Anton N. Kazantsev	Cardiovascular Surgeon, Department of Surgery No. 3, Aleksandrovsky City Hospital; https://orcid.org/0000-0002-1115-609X, dr.antonio.kazantsev@mail.ru; 20%, performing operations, writing an article, approving the final version of the article
Roman A. Vinogradov	Doctor of Medical Sciences, Head of Department of Cardiovascular Surgery, S.V. Ochapovsky Research Institute-Regional Clinical Hospital No. 1; http://orcid.org/0000-0001-9421-586X, viromal@mail.ru; 19%, concept and design, article writing, approval of the final version of the article
Yuri N. Zakharov	Doctor of Physical and Mathematical Sciences, Head of the Department Kemerovo State Medical University; http://orcid.org/0000-0002-2895-1428, zaxarovyn@yandex.ru; 18%, concept and design, approval of the final version of the article
Vladimir G. Borisov	Candidate of Physical and Mathematical Sciences, Kemerovo State Medical University; http://orcid.org/0000-0002-9117-9661, aaapppmmmooo@rambler.ru; 14%, concept and design, approval of the final version of the article

Mikhail A. Chernyavsky	Doctor of Medical Sciences, Head of the Research Department of Vascular and Interventional Surgery, V.A. Almazov National Medical Research Center; http://orcid.org/0000-0003-1214-0150, GibridSSH2@yandex.ru 7%, writing an article, approval of the final version of the article
Vyacheslav N. Kravchuk	Doctor of Medical Sciences, Professor, Head of the Department of Cardiovascular Surgery, I.I. Mechnikov North-Western State Medical University; http://orcid.org/0000-0002-6337-104X, kravchuk9@yandex.ru; 6%, writing an article, approval of the final version of the article
Dmitry V. Shmatov	Doctor of Medical Sciences, Professor, Deputy Chief Physician for Cardiac Surgery, N.I. Pirogov Clinic of High Medical Technologies, St. Petersburg State University; https://orcid.org/0000-0002-1296-8161, dv.shmatov@gmail.com; 5%, concept and design, approval of the final version of the article
Konstantin P. Chernykh	Cardiovascular Surgeon, Department of Surgery No. 3, Alexandrovsky City Hospital; https://orcid.org/0000-0002-5089-5549, cvs.doc@yandex.ru; 4%, performing operations, writing an article, correcting an article, approving the final version of an article
Andrey A. Sorokin	Cardiovascular Surgeon, N.I. Pirogov Clinic of High Medical Technologies, St. Petersburg State University; https://orcid.org/0000-0003-0493-4209, sorokin@gmail.com; 3%, execution of operations, correction of the article, approval of the final version of the article
Goderzi Sh. Bagdavadze	Resident, N.D. Monastyrsky Department of Surgery, I.I. Mechnikov North-Western State Medical University; https: //orcid.org/0000-0001-5970-6209, gud_777@bk.ru; 2%, execution of operations, correction of the article, approval of the final version of the article
Sergey V. Artyukhov	Candidate of Medical Sciences, Head of the Operating Unit, Alexandrovsky City Hospital; http://orcid.org/0000-0001-8249-3790, art_serg@mail.ru; 1%, concept and design, approval of the final version of the article
Gennady G. Khubulava	Doctor of Medical Sciences, Professor, Head of the P.A. Kupriyanov First Department and Surgery Clinic of Advanced Training for Doctors, S.M. Kirov Military Medical Academy; http://orcid.org/0000-0002-9242-9941, ggkh07@rambler.ru; 1%, concept and design, correction of the article, approval of the final version of the article

AG – angiography
ASP – atherosclerotic plaque
BCA – brachiocephalic arteries
CCA – common carotid artery
CEE – carotid endarterectomy
CDS – color duplex scanning
ECA – external carotid artery
ICA – internal carotid artery
MSCT AG – multispiral computed tomography with angiography

INTRODUCTION

Carotid endarterectomy (CEE) has become a routine intervention on the carotid arteries in many vascular hospitals in our country [1-3]. National guidelines provide strict quality standards for this procedure [1]. There are known permissible rates of the frequency of possible adverse cardiovascular events for institutions that are engaged in reconstructive interventions on the brachiocephalic arteries (BCA) [1]. However, no criteria have been developed for restenosis of the internal carotid artery (ICA) [1]. Despite this, there are large studies and meta-analyzes that have concluded that early and late loss of vessel lumen is an important predictor of ischemic stroke [4–7]. Most of these works demonstrate a high tendency to form this pathology after classical CEE relative to eversion technique [4–7]. According to a number of authors, the physical distortion of the properties of the blood flow after the expansion of the carotid bulb forms zones of parietal stagnation and turbulent flow, which provokes neointimal hyperplasia in this localization. [8–11]. However, ICA restenosis is formed, according to various sources, only in 5–20% of cases from the total sample [2, 4, 12–14]. A possible reason is that the width of the patch does not always dilate the lumen of the artery to those sizes that distort hemocirculation with the induction of subsequent pathological phenomena [2, 8–10, 12]. To date, the current recommendations do not offer methods that can differentiate this cohort of patients with the aim of further precision management and early detection of vascular lumen loss [1].

The purpose of this paper was to demonstrate the effectiveness of the developed computer modeling technique for predicting the likelihood of ICA restenosis after classical CEE.

Clinical case

Patient V., 62 years old, a man, complained of dizziness, tinnitus, anginal pain in the heart during exercise. Using screening color duplex scanning (CDS), stenotic lesion of the right ICA was diagnosed. According to the results of coronary angiography, hemodynamically significant stenoses were not revealed. According to angiography (AG), 70% stenosis of the right ICA with signs of unstable atherosclerotic plaque (ASP) was visualized (Fig. 1).

Fig. 1. Angiography of the brachiocephalic arteries: 1 — 70% stenosis of the right internal carotid artery.

A multidisciplinary council including a cardiovascular surgeon, endovascular surgeon, neurosurgeon, cardiologist, neurologist, anesthesiologist-resuscitator, in view of the presence of an extended atherosclerotic lesion of carotid bifurcation made a decision to perform the planned classical CEE on the right with the reconstruction with a patch made of diepoxy-treated xenopericardium. The postoperative period was uneventful. To control the patency of the reconstruction zone, the patient underwent multislice computed tomography with angiography (MSCT AG). According to the study, no signs of restenosis were revealed (Fig. 2).

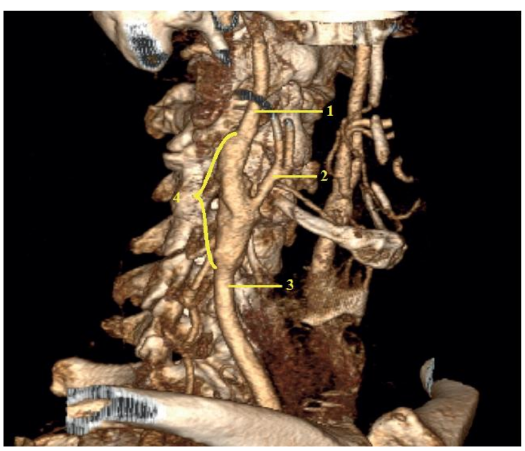

Fig. 2. Multislice computed tomography with angiography of the brachiocephalic arteries: 1 — internal carotid artery; 2 — external carotid artery; 3 — common carotid artery; 4 — patch implantation area.

In order to identify the risks of carotid restenosis formation in the mid-term and long-term follow-up periods, the MSCT AG data (with a layer thickness of 0.6 mm and a current of 355 mA) were used for computer modeling of the reconstruction zone of the carotid bifurcation of a real patient. The files in the *.dcm* format were processed using the *Sim Vascular* software, and then a geometric model was built (Fig. 3).

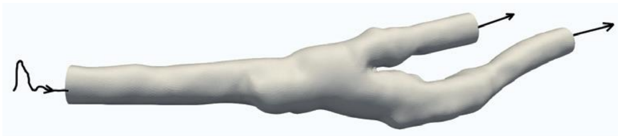

Fig. 3. Geometric model of the right internal carotid artery after carotid endarterectomy with plastic xenopericardial patch

Further, to build a model of currents, the CDS of the reconstruction zone was performed in three sections: 1. in the proximal section of the common carotid artery (CCA) (3 cm proximal to the bifurcation); 2. in the section of the external carotid artery (ECA), 2 cm distal to the carotid sinus; 3. in the section of the ICA 2 cm distal to the carotid sinus. Due to the fact that recirculation occurs in the carotid sinus, which distorts the data on the main flow, the most optimal segment for measuring indicators is precisely the distance 2 cm distal to the carotid sinus. The incoming flow was modeled in accordance with the velocity flow diagrams in the CCA (Fig. 4).

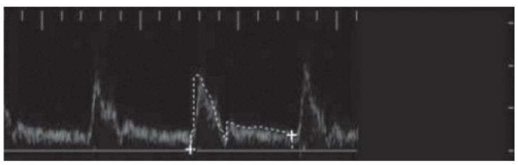

Fig. 4. Velocity diagram of the flow in the common carotid artery

The data (*TAPV* and *Area*) from the ICA and the ECA were used to form the correct distribution of the outgoing flows between these vessels (Fig. 5).

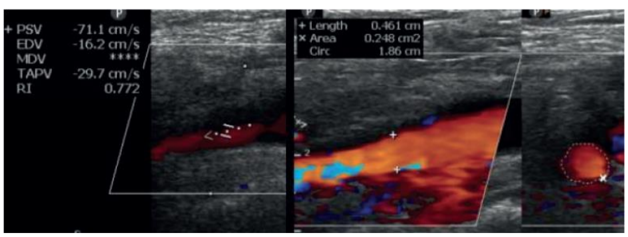

Fig. 5. *TAPV* and *Area* data for the internal and external carotid arteries

Then the obtained CDS data and the mesh of the geometric model were loaded into the *Open Foam* program. The first step was to build blood flow lines. The color gradation shows the speed of movement of particles along the trajectory: blue - slowly, red - fast (Fig. 6).

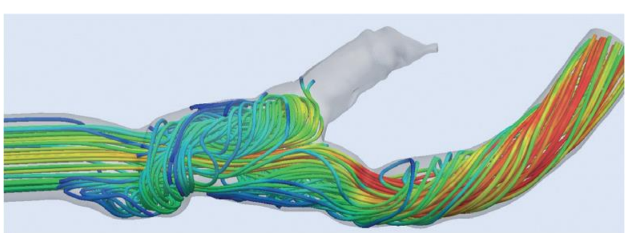

Fig. 6. Construction of streamlines

After that, the velocity field was constructed in various planes. The arrows showed the direction of the projection of the velocity vector on the given plane, the color gradation showed the value of the blood flow velocity at a given point in accordance with the scale (Fig. 7).

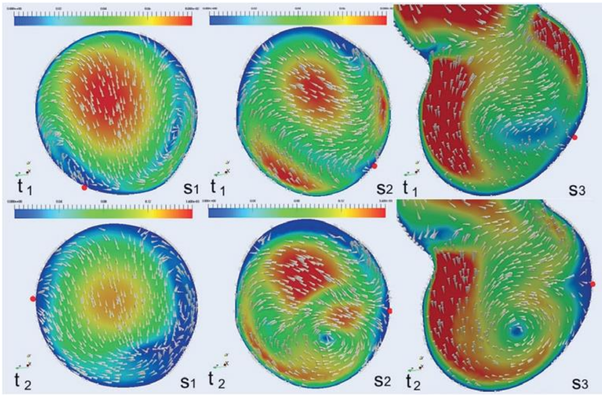

Fig. 7. Construction of the velocity field in different planes

Diagrams of this kind demonstrated the recirculation zones and flow branching zones on the vessel wall (red dots).

Then, in the post-processing mode, the hemodynamic characteristics on the vessel wall were plotted based on the results of the obtained calculations. Fig. 8 shows the distribution of the *RRT* index: red and yellow - areas of increased risk of restenosis.

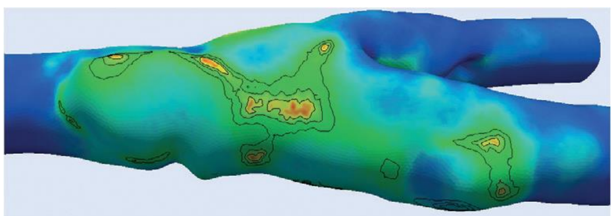

Fig. 8. Distribution of the *RRT* indicator: red and yellow - areas of increased risk of restenosis

Fig. 9 shows the vector field of the *TAWSS* index, which reflects the direction of the parietal movement of blood particles. The lines represent the division of the vessel wall into zones of parietal stagnation and turbulence. Pink - the area of attraction of a stable stationary point (red point in this zone).

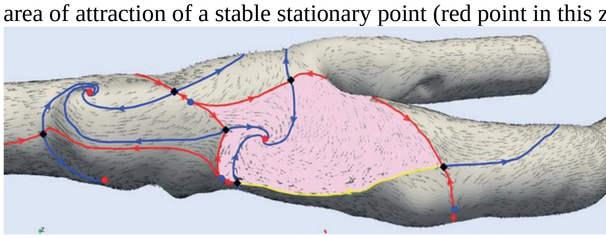

Fig. 9. Vector field of the *TAWSS* index, which reflects the direction of the parietal movement of blood particles

Thus, in this patient, when analyzing the *RRT* and *TAWSS* indicators, 5 zones of increased risk of restenosis formation were identified, 3 of which are localized in the ICA (Fig. 10).

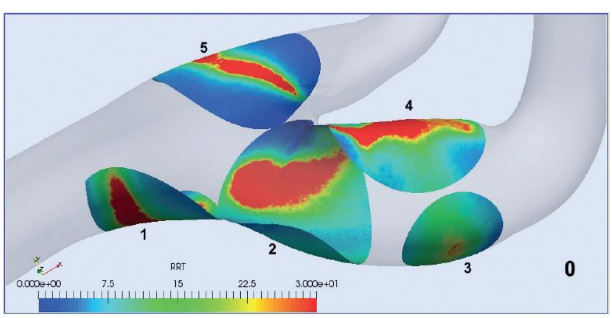

Fig. 10. Areas of increased risk of restenosis formation

Six months after CEE, the patient was invited to the clinic for a control CDS of the reconstruction zone, according to which hemodynamically significant restenosis of the right ICA was diagnosed. According to the results of MSCT AG, 80% restenosis was visualized (Fig. 11). It should be noted that the localization of the lesion corresponded to the 3rd and 4th risk zones, as was indicated in Fig. 10.

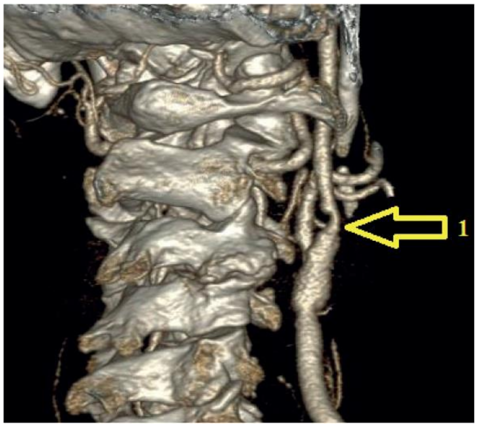

Fig. 11. Multislice computed tomography with angiography of the brachiocephalic arteries 6 months after carotid endaterectomy: 1 — 80% restenosis of the right internal carotid artery

The patient was admitted to the hospital for a classic right-sided reCEE. The postoperative period was uneventful. The patient was discharged on the 7th day after surgery.

DISCUSSION

According to national recommendations, the choice of the type of CEE is carried out only by the operating surgeon [1]. When deciding in favor of the classical technique, as a rule, a biological, synthetic or autovenous patch is used [1]. The width of the latter in the first 2 cases has standard factory values. However, the diameter of an artery can vary significantly from person to person [8–10]. It follows from this that there can be no universal patch size. Therefore, in some situations, the vascular surgeon reduces the width of the patch so that it does not unnecessarily dilate the carotid bulb [2]. But today there is no single technique and rules by which a personalized patch size can be established [1]. It follows that the latter is calibrated based on the operator's experience in the *"hand-made"* format. In the context of evidence-based medicine, this approach cannot be justified. The current situation requires the development of new principles and methods that will meet the requirements of personalized medicine. The presented method of computer modeling has demonstrated the possibility of predicting the development of restenosis after classical CEE. In the same way, using the MSCT AG data of the patient's ICA before surgery, it is possible to remove in a virtual format atherosclerotic plaques, project an arteriotomy line, and implant patches of different sizes. This approach allows you to select the most suitable reconstruction model, characterized by minimal deformation of the physical properties of the blood flow. However, it must be remembered that not always the vascular surgeon will be able to implement the parameters set by the computer program with millimeter accuracy. In any case, the arteriotomy line, as well as the calibration of the patch, will be carried out by the operator himself. Therefore, in the future, two directions of further development of a personified approach in carotid surgery are possible: 1. the patch will be made individually, at the factory stage, according to the data provided by the computer model; 2. the CEE itself will be carried out by a robot. The topographic localization of the carotid bifurcation and the peculiarities of the local anatomy allow an experienced vascular surgeon to isolate the latter in 5-10 minutes, which significantly differs in duration from the approaches, for example, to the abdominal aorta. The CEE duration time most often from the incision to the skin sutures does not exceed 1-1.5 hours. Today, the progress of medical technology has reached the point that the use of a robotic surgeon (*Da Vinci, Intuitive Surgical*, USA) is possible in complex operations on the aorta [15, 16]. Thus, it is only a matter of time before the use of robotic technology in the CEE - an operation that has actually become a "conveyor belt". In the future, the collaboration of this possibility with the results of computer modeling will allow, with maximum accuracy, excluding possible erroneous "preferences" of a person, to carry out a personalized CEE, increasing the established quality standards.

CONCLUSION

The demonstrated method of computer modeling on the presented clinical example has confirmed its effectiveness in predicting carotid restenosis after classical carotid endarterectomy. Routine application of this technique among the entire cohort of patients after reconstructive interventions on the brachiocephalic arteries will make it possible to identify patients with a high risk of developing vascular lumen loss, to carry out their precise supervision in the mid- and long-term follow-up periods, avoiding the development of ischemic events.

REFERENCES

1. *Natsional'nye rekomendatsii po vedeniyu patsientov s zabolevaniyami brakhiotsefal'nykh arteriy.* at: http://www.angiolsurgery.org/recommendations/2013/recommendations_brachiocephalic.pdf [Accessed 20 May 2021] (in Russ.).
2. Kazantsev AN, Tarasov RS, Burkov NN, Shabaev AR, Lider RYu, Mironov AV. Carotid endarterectomy: three-year results of follow up within the framework of a single-centre register. *Angiology and Vascular Surgery*. 2018;24(3):101–108. (in Russ.)
3. Vinogradov RA, Matusevich VV. Carotid body saving techniques in carotid artery surgery. *Medical News of the North Caucasus*. 2017;12(4):467–468. (In Russ.). https://doi.org/10.14300/mnnc.2017.12130
4. Gavrilenko AV, Kuklin AV, Al-Yousef NN, Wang Xiaochen, Bulatova LR, Li Rui. Meta-Analysis of the Results of Eversion Carotid Endarterectomy and Endarterectomy with Patch Plasty. *Angiology and Vascular Surgery*. 2020;26(1):176–183. (In Russ.) http://doi.org/10.33529/ANGIO2020121
5. Dudanov IP, Abuazab BS, Akhmetov VV. Comparative characteristics of classical and eversion endarterectomy of the carotid arteries. *Research'n Practical Medicine Journal*. 2017;4(3):8–15. (in Russ.). https://doi.org/10.17709/2409-2231-2017-4-3-1
6. Kazantsev AN, Chernykh KP, Lider RYu, Bagdavadze GSh, Andreychuk KA, Kalinin EYu, et al. Comparative results of conventional and eversion carotid endarterectomy. *Kardiologiya i Serdechno-Sosudistaya Khirurgiya*. 2020;13(6):550–555. (in Russ.) https://doi.org/10.17116/kardio202013061550
7. Bockeria LA, Bakhmet'ev AS, Kovalenko VI, Temrezov MB, Shumilina MV, Chekhonatskaya ML. The Choice of Carotid Endarterectomy Method in Atherosclerotic Disease of Internal Carotid Artery. *Annals of Surgery (Russia)*. 2017;22(5):265–271. (in Russ.). https://doi.org/10.18821/1560-9502-2017-22-5-265-271
8. Demirel S, Chen D, Mei Y, Partovi S, von Tengg-Kobligk H, Dadrich M, et al. Comparison of morphological and rheological conditions between conventional and eversion carotid endarterectomy using computational fluid dynamics a pilot study. *Vascular*. 2015;23(5):474–482. PMID: 25298137 https://doi.org/10.1177/1708538114552836
9. Domanin M, Bissacco D, Le Van D, Vergara C. Computational fluid dynamic comparison between patch-based and primary closure techniques after carotid endarterectomy. *J Vasc Surg*. 2018;67(3):887–897. PMID: 29246640 https://doi.org/ 10.1016/j.jvs.2017.08.094
10. Guerciotti B, Vergara C, Azzimonti L, Forzenigo L, Buora A, Biondetti P, et al. Computational study of the fluid-dynamics in carotids before and after endarterectomy. *J Biomech*. 2016;49(1):26–38. PMID: 26617369 https://doi.org/10.1016/j.jbiomech.2015.11.009
11. Ištvanić T, Vrselja Z, Brkić H, Radić R, Lekšan I, Curic G. Extended Eversion Carotid Endarterectomy: Computation of Hemodynamics. *Ann Vasc Surg*. 2015;29(8):1598–1605. PMID: 26319145 https://doi.org/10.1016/j.avsg.2015.05.034
12. Kazantsev AN, Bogomolova AV, Burkov NN, Bayandin MS, Grishchenko EV, Guselnikova YuI, et al. Morphological features of restenosis after carotid endarterectomy with diepoxide-treated xenopericardial patch angioplasty. *Kardiologiya i Serdechno-Sosudistaya Khirurgiya*. 2020;13(1):68–71. (in Russ.) https://doi.org/10.17116/kardio20201301168
13. Liu D, Li ZL, Wang M, Wu RD, Wang JS, Wang SM, et al. Comparative Analysis of Patch Angioplasty Versus Selective Primary Closure During Carotid Endarterectomy Performed at a Single Vascular Centre in China. *Ann Vasc Surg*. 2020:S0890-5096(20)31079-7. PMID: 33383139 https://doi.org/10.1016/j.avsg.2020.11.036
14. Lazarides MK, Christaina E, Argyriou C, Georgakarakos E, Tripsianis G, Georgiadis GS. Network Meta-Analysis of Carotid Endarterectomy Closure Techniques. *Eur J Vasc Endovasc Surg*. 2021;61(2):181–190. PMID: 33257115 https://doi.org/ 10.1016/j.ejvs.2020.10.009
15. Helgetveit I, Krog AH. Totally laparoscopic aortobifemoral bypass surgery in the treatment of aortoiliac occlusive disease or abdominal aortic aneurysms – a systematic review and critical appraisal of literature. *Vasc Health Risk Manag.* 2017;13:187–199. PMID: 28572732. https://doi.org/10.2147/VHRM.S130707
16. Colvard B, Georg Y, Lejay A, Ricco JB, Swanstrom L, Lee J, et al. Total robotic iliac aneurysm repair with preservation of the internal iliac artery using sutureless vascular anastomosis. *J Vasc Surg Cases Innov Tech.* 2019;5(3):218–224. PMID: 31297470 https://doi.org/10.1016/j.jvscit.2019.01.001

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