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USING A NEW SELECTIVE ANTEGRADE CEREBRAL PERFUSION TECHNIQUE FOR ASCENDING AORTA AND AORTIC ARCH REPAIR

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Dissecting aortic aneurysm is one of the most dangerous diseases of the aorta, often leading to severe complications or death. Currently, due to the increased level of diagnosis and the speed of care for patients with aortic diseases, there is now a need to improve approaches to the treatment of this condition. This paper presents the outcomes of a technique developed at our center, Shumakov National Medical Research Center of Transplantology and Artificial Organs, for selective antegrade cerebral perfusion (SACP) when performing prosthetic replacement of the aortic arch under circulatory arrest. Surgical treatment is performed on an emergency basis. During these surgeries, we focused on preventing neurological complications. Analysis of the efficacy and safety of our SACP technique shows that we obtained positive outcomes. In the analysis of 10 cases of aortic arch replacement, there was no evidence indicating the presence of any neurological complication. This technique allows for more adequate monitoring of perfusion during reconstructive interventions on the ascending aorta and aortic arch than the classical perfusion technique.

Keywords: ascending aorta and aortic arch repair, dissecting aortic aneurysm, selective antegrade cerebral perfusion, circulatory arrest, ischemic brain injury.

Aortic arch surgery remains one of the most complex areas of cardiac surgery. Dissecting aneurysm is the main condition requiring surgical intervention on the ascending aorta and aortic arch (Fig. 1).

Aortic dissection (AD) is the formation of a tear in the inner elastic layer of the aorta with subsequent blood inflow into the degeneratively altered middle layer, formation of intramural hematoma and spread to the inner and outer layers with the formation of an additional intravascular channel (false lumen) (Fig. 2). Dissection occurs more commonly in the distal (antegrade) direction, less common in the proximal (retrograde) direction [1, 2].

Dissecting aortic aneurysm is a medical emergency (requiring surgical correction as soon as possible) that, even with optimal treatment, can quickly lead to death. If AD goes through all the three layers of the aorta, a complete tear through all the layers occurs, resulting in massive bleeding. Aortic rupture carries a mortality rate of 80%, and half of patients die in the prehospital phase [3, 6–10].

Arterial hypertension is one of the main causes of dissecting aneurysms. Most patients with AD have this disease. Connective tissue dysplasia and congenital diseases are often combined with Marfan syndrome, Ehlers–Danloh syndrome, congenital bicuspid aortic valve, aortic coarctation, Turner syndrome, giant cell aortitis and recurrent polychondritis and other diseases, which are also important factors in dissecting aneurysms.

Pregnancy is also a risk factor for AD; 50% of AD afflicting women younger than 40 years are pregnancy associated, the highest incidence being in the third trimester [2–7]. Aortitis, blunt chest trauma, aortic atherosclerosis combined with hypertension and preeclampsia in pregnant women are also accompanied by aortic dissection and even aortic aneurysm rupture as a complication [2, 4, 5].

Dissecting aortic aneurysms have been reported following surgical procedures where counterpulsation devices are inserted into the aorta, or the aorta or its major branches are cannulated. It is believed that iatrogenic dissecting aortic aneurysm is a rare complication. Unlike the spontaneous one, iatrogenic dissection is observed in older age groups and is more often accompanied by atherosclerosis. Trauma rarely leads to dissecting aneurysm [4–10].

The classification of dissecting aortic aneurysms is based on the localization of the proximal intima tear and the extent of dissection.

The AD classification proposed by Michael Ellis DeBakey (1965) (Fig. 3) provides an anatomical description of the dissection variants. They divided dissection according to the site of onset and extent of dissection:

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Type I – onset of dissection in the ascending aorta, further extends to the aortic arch and often distally beyond;

Type II – confined to the ascending aorta;

Type III – onset in the descending aorta, but spreads distally, rarely spreading proximally.

According to the Stanford classification of AD (1970), all cases of aortic tears can be divided into two groups – A and B, depending on which section of the aorta is involved.

Group A involves dissection in the ascending aorta and/or aortic arch and possibly the descending aorta. It includes DeBakey types I, II, and III. Retrograde dissection (occurring in the descending aorta or aortic arch, but spreading to the ascending aorta) is also possible.

Group B involves dissection in the descending aorta (distal to the origin of the left subclavian artery), without involvement of the ascending aorta or aortic arch. It includes DeBakey type III without retrograde continuation into the ascending aorta [2, 6, 7, 10].

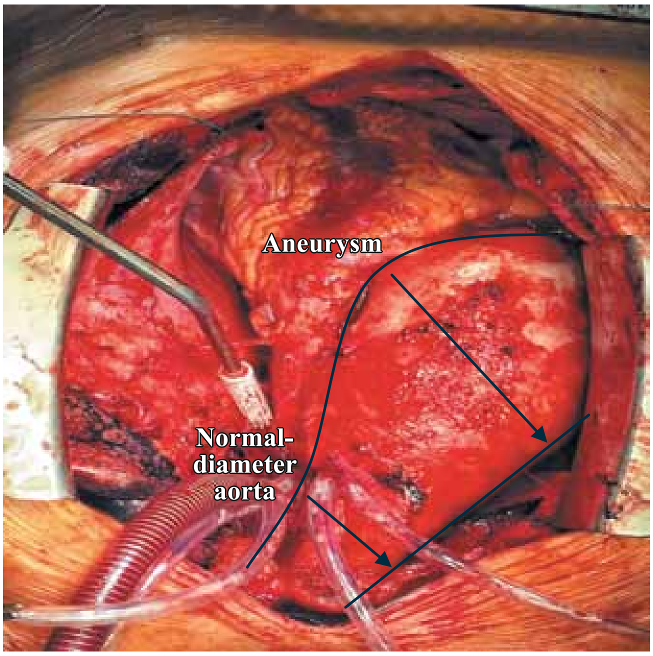

Fig. 1. Aortic aneurysm

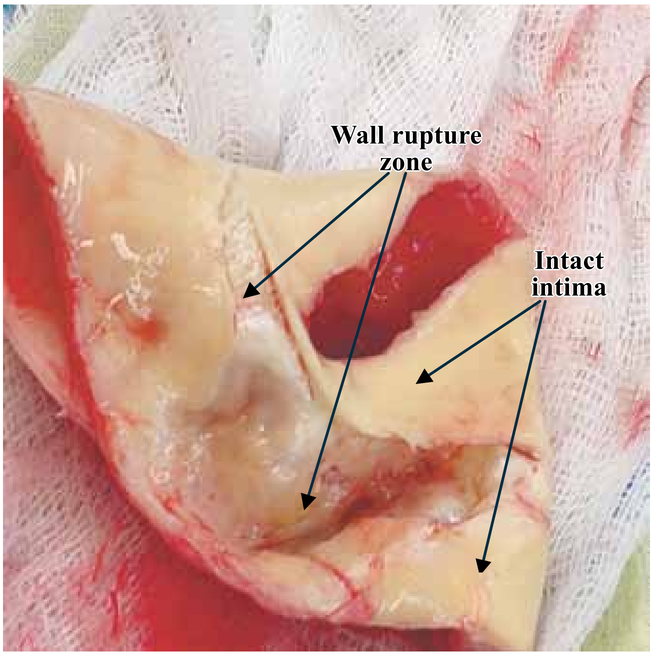

Fig. 2. Excised section of the dissected ascending aorta

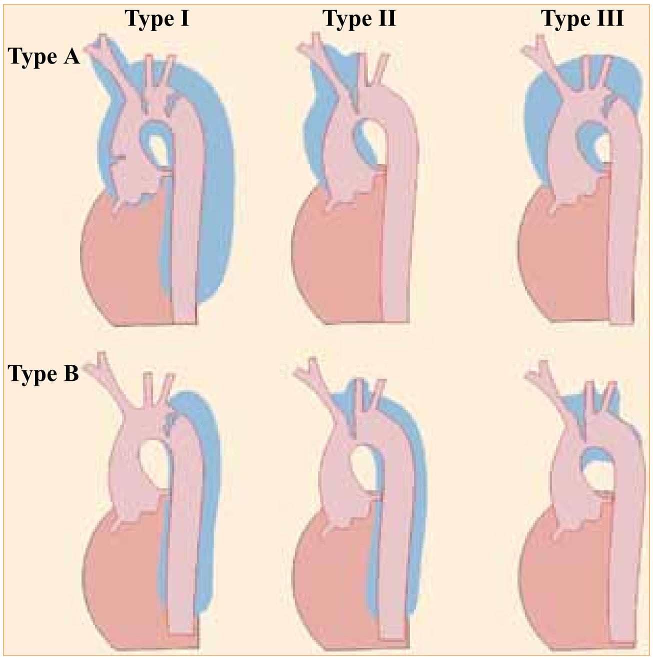

Fig. 3. Classification of aortic dissections by prevalence: DeBakey (1965) and Stanford (1970)

Currently, two main mechanisms of dissecting aneurysm formation are considered: aortic intima rupture or stretching and intramural hematoma development. This mechanism is the most common and is more frequently mentioned in literature. Aortic endothelial layer rupture usually occurs due to hypertension and/or dilatation of the vessel. The aortic layers separate due to the impact of pulse wave. The most common intima rupture forms in the ascending aorta, immediately above its sinuses. In 60% of cases, the tear is localized on the anterior surface of the ascending aorta, distal to the left subclavian artery in 30%, and within the aortic arch in 10% [6, 10].

Much more complicated is the second AD mechanism. The rupture of vasa vasorum and, as a consequence, formation of intramural hematoma, spreading within the middle layer of the aortic wall, leads to intima rupture. This mechanism occurs in no more than 10% of cases.

Despite advances and improvements in surgical and perfusion techniques over the past 30 years, mortality, morbidity and, in particular, incidence of cerebral complications, remain higher than for procedures performed on the more proximal aorta. Traditional approaches in the prevention of cerebral injury have focused on the use of the following concepts during aortic arch replacement: deep hypothermic circulatory arrest (10–15 °C), retrograde cerebral perfusion through jugular veins under moderate hypothermic circulatory arrest (25–30 °C), and selective antegrade cerebral perfusion under moderate hypothermic circulatory arrest (25–30 °C) – a technique that most world clinics now follow [11].

WAYS TO PROTECT THE BRAIN

Deep hypothermic circulatory arrest (DHCA) confers advantages to the surgeon, allowing work to be done in a bloodless and cannula-free operating field. However, there are a number of significant disadvantages. First, the cooling and warming process increases cardiopulmonary bypass (CPB) time significantly and leads to associated postoperative organ dysfunction. Severe coagulopathy and increased associated risks of uncontrolled spontaneous bleeding also develop [11]. Secondly, during the warming period, there is a probability of ischemic cerebral reperfusion injury [12], disruption of the normal mechanisms of cerebral circulation regulation and formation of excessive cerebral temperature gradients [13], which aggravate other sources of cerebral injury. Thirdly, the formation of anastomoses by open technique during DHCA increases the risk of material and air emboli entering both cerebral and distal vessels. The time available for performing complex aortic arch reconstruction during DHCA is limited, as prolonged periods of arrest are associated with a proportional increase in the incidence of cerebral and target organ injury [14]. It should be noted that minimal impairment of brain function can occur with DHCA lasting even 20 minutes [10]. This potentially indicates that any period of DHCA can cause adverse neurological outcomes. Such time limitation can lead to technically imperfect aortic arch reconstruction, which in turn can lead to early or late complications.

In an attempt to ensure adequate cerebral blood flow and thus prolong the "safe" DHCA period, many centers have introduced adjuvant cerebral perfusion techniques. Some centers dealing with aortic surgery in large volumes have successfully adapted the use of retrograde cerebral perfusion (RCP) in combination with DHCA [13]. However, there are currently published experimental and clinical studies showing a limited supply of nutrients to the brain in the RCP and suggesting excessive retrograde perfusion pressure and associated cerebral edema that aggravate cerebral injury [4, 5].

In contrast to RCP, SACP is more widely used and provides adequate cerebral blood flow [8]. The methods fall into 2 main groups: 1) separate cannulation of individual vessels, and 2) use of cannulation sites of aortic arch branches such as the axillary, innominate or carotid artery. Nevertheless, both methods have their disadvantages. Direct cannulation of branches through the open arch can lead to atheromatous and air embolism. In addition, since there are periods of circulatory arrest before and after perfusion cannula insertion, deep hypothermia is necessary. On the other hand, catheterization of aortic arch branches in the periphery of the operative field (e.g., axillary artery) avoids many of these disadvantages, but has its own. Aortic arch reconstruction period is performed with a single inflow and depends on collaterals potentially providing flow transfer to the contralateral hemisphere. This creates the possibility of ipsilateral hypoperfusion and/or contralateral hyperperfusion, depending on whether the flow is excessive or too lean.

It is important to note that both antegrade and retrograde cerebral perfusions do not provide perfusion of other vital organs; they rely entirely on deep hypothermia to protect such organs as kidneys, liver and spinal cord. It is sometimes claimed that SACP provides perfusion of distal organs through upper and lower body collaterals [13]. However, it is questionable whether such a collateral flow provides real nutrient flow under open distal anastomosis, when most of the flow inevitably goes through the path of least resistance – directly into CPB pump suctions. It is important to note that vital organ malperfusion can easily go unnoticed because the consequences are not as obvious as acute stroke. But despite this, its effects can be just as dangerous, manifesting as coagulopathy, gastrointestinal bleeding, sepsis and multiple organ failure [5].

The aim of this study is to analyze our own experience with the original SACP technique in ascending aorta and aortic arch repair to solve the problems of improving the protocol of perfusion support for surgical reconstruction of the aortic arch and the procedure as a whole.

MATERIALS AND METHODS

The retrospective study included 10 patients who underwent reconstructive operations on the ascending aorta and aortic arch between 2019 and 2021 under CPB, circulatory arrest, and SACP using the technique we developed, patent No. RU2734136C1.

The currently known SACP techniques do not allow control of the volume perfusion rate in isolation in the arteries of each cerebral hemisphere; they also do not allow accurate assessment of perfusion pressure in the brachiocephalic trunk (BCA) and the left common carotid artery (LCCA). After cessation of circulatory arrest, pressure control in the BCA and LCCA is possible only with the help of an occluder on the cerebral perfusion line or in one common line, which is bifurcated on the operating table using an adapter – a tee. The available techniques do not allow separate control and correction of the patient's brain and body temperature.

In addition, the known methods are complicated because they require Doppler ultrasound of the BCA, LCCA, and left axillary artery, as well as transcranial Doppler ultrasound of the middle cerebral artery.

In this regard, the bilateral SACP technique developed at Shumakov National Medical Research Center of Transplantology and Artificial Organs was used.

This method allows cerebral perfusion by a bilateral selective cerebral perfusion system combined with a physiological unit such that it becomes possible to perform separate supply of oxygenated blood through the BCA and LCCA with a given volumetric rate and temperature under pressure control in each line (Fig. 4).

This system includes: cardiotomy reservoir (1), first pump (2), oxygenator (3) whose exit is connected to an arterial trunk port (6), LCCA port (17), BCA port (18), second pump (11), characterized by the fact that it further includes a circulation reservoir (7), heat exchanger (9), third pump (12), first (5), second (13) and third (14) pressure sensors, six 4, 8, 10, 15, 16, 19 branch tees, wherein the outlet of the oxygenator (3) is connected in series with the arterial trunk port (6) through the first branch tee (4) and the first pressure sensor (5), one port of the first branch tee (4) is connected to the first port of the second branch tee (8), which consistently connects the inlets of the circulation reservoir (7) and heat exchanger (9); the outlet of the heat exchanger (9) through the third tee (10) is connected to the LCCA and BCA ports by individual lines, one of which contains the second pump (11) and the second pressure sensor (13), and the other contains the third pump (12) and the third pressure sensor (14), and the output of the circulation reservoir (7) is connected through the fourth (15), fifth (16) and sixth (20) tees to the LCCA and BCA lines.

The advantage of the bilateral SACP system used lies with the possibility of isolated control and correction of the volumetric perfusion rate and perfusion pressure in both cerebral hemispheres, as well as independent thermoregulation of the circulatory circuits of the patient's brain and body.

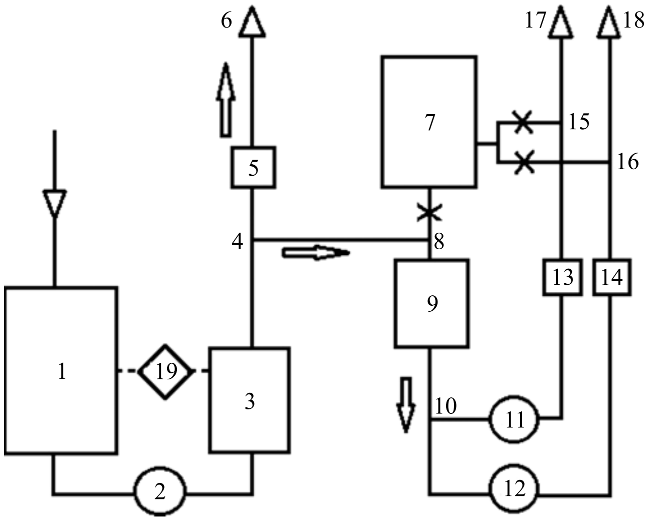

Fig. 4. System for bilateral selective antegrade cerebral perfusion during reconstructive surgery on the aortic arch under cardiopulmonary bypass

The medical and technical outcome is to prevent and reduce neurological complications, decrease the frequency of multiple organ failure, provide for early patient activation and is aimed at reducing hospital mortality during operations on the aortic arch and its branches, performed under hypothermic circulatory arrest with cold cardioplegia due to prolonged hypothermia at the stage of patient warming, control of perfusion rate and pressure in the arteries of each cerebral hemisphere.

The stage of intervention on the ascending aorta consisted of supracoronary ascending aortic replacement, aortic root replacement with a valvulated tube with implantation of coronary artery orifices into it (according to Hugh Bentall and Antony De Bono procedure). The stage of intervention on the aortic arch consisted of full or partial aortic arch replacement with a multibranched prosthesis. In the presence of descending thoracic aortic dissection, Hans Borst's elephant trunk procedure was used to stop the false channel function.

RESULTS

This article also presents analysis of the case histories of 10 patients admitted with De Bakey type I and type II aortic dissection.

There were 5 male and 5 female patients. The average age of the patients was 51.2 ± 14.5 years.

Of the entire group, 10% (1 patient) underwent reoperation under CPB (aortic root reimplantation by David procedure with Gelweave-30 synthetic prosthesis, mitral valve annuloplasty with MedInj-34 support ring, tricuspid valve annuloplasty with MedInj-30 support ring and exoprosthetic repair of the ascending aorta and aortic arch with Gelweave-32 synthetic prosthesis under CPB, circulatory arrest and SACP); the remaining 90% were operated on initially.

Among all patients, 40% had chest pains on admission. At the same time, 70% of the patients complained of shortness of breath of varying intensity. Pathological aortic murmurs during initial examination were detected in 4 patients out of 10. Three patients were hospitalized in severe conditions and underwent emergency surgery for life-threatening indicators. It is worth noting that there were preoperative rhythm disturbances in 30% of patients, where 20% initially had atrial fibrillation and 10% had supraventricular extrasystole. No rhythm disturbances were noted in the remaining patients. The mean heart rate (HR) was ~72 ± 16.37 bpm. Preoperative examination of patients included echo and chest MSCT with intravenous contrast. The mean diameter of the aortic valve fibrous ring (FR) was 2.36 ± 0.13 cm; that of the sinotubular junction (STJ) was 3.91 ± 0.59 cm; mean diameters of the ascending aorta and aortic arch were 5.63 ± 1.05 and 3.8 ± 0.45 cm, respectively. Analysis of left ventricular (LV) volume fractions showed:

mean end-diastolic volume (EDV) of 133.9 ± 57.3 mL; mean end-systolic volume (ESV) of 58.2 ± 28.69 mL; mean Stroke volume (SV) of 75.8 ± 28.35 mL; and mean ejection fraction (EF) of 55.7 ± 7.44%. In 70% of cases, 50 to 100 mL of fluid was found in the pericardial cavity according to echo. Patients with bicuspid aortic valve (AV) were found in 20% of the examined patients, whereas the majority were patients with tricuspid. The mean peak gradient was 10.07 ± 3.66 mm Hg. Most patients (70%) had grade 2 aortic regurgitation; in the mitral valve (MV), 80% had grade 1 regurgitation. There were two cases of grade 2 regurgitation, and one of them had previously undergone MV repair with the use of an annuloplasty ring. Phenomena of group 1 pulmonary arterial hypertension were observed in 30% of patients.

According to MSCT data, aortic dissection on CT scan was detected in all patients; 80% had DeBakey type I AD, and 20% had type II AD.

The extent of surgical intervention in the selected patients was distributed as follows:

– 40% had supracoronary ascending aortic and aortic arch replacement (Fig. 5, a);
– 20% had supracoronary ascending aortic and hemiarch replacement (Fig. 5, b);
– 10% had ascending aorta replacement with a valvulated tube with implantation of coronary artery orifices according to Kouchoukos procedure + aortic arch replacement;
– 30% had aortic arch replacement with multibranched prosthesis by lowering the synthetic prosthesis into the descending thoracic aorta according to Hans Borst's elephant trunk procedure (Fig. 5, c).

The above surgeries lasted for an average of 326.5 ± 62.10 minutes. The aortic clamping time averaged 94.2 ± 45.34 minutes. Selective cerebral perfusion time was 49.4 ± 40.78 minutes on average. All surgeries were also performed under moderate hypothermia, with an average temperature of 25.9 ± 2.06 °C.

All patients required cardiotonic support after surgery, predominantly with dopamine at an average dose of 3.6 μg/kg/min, and dobutamine at an average dose of 2.25 μg/kg/min. In two cases, adrenaline was administered at 80 and 10 ng/kg/min, respectively. It should be noted that both cases of adrenaline use were in patients who underwent emergency surgery for life-threatening indicators.

Perfusion rate and flow (Table 1) reflect the quality of myocardial protection. Coronary perfusion was performed by selective antegrade in all 10 cases. Custodiol solution (2 L) was used for cardioplegia in 30% of cases, and Calafiore blood-based potassium cardioplegic solution was used in the remaining cases.

Table 1 indicates that the mean values of coronary artery perfusion were within acceptable range in all episodes of cardioplegia. In particular, the absence of high resistance in the coronary arteries and optimal flow rates through both cannulas indicate the adequacy of myocardial protection during the above-mentioned operations. Cardioplegia was performed with a solution based on 15% KCL + $MgSO_4$ + lidocaine at a perfusion rate of 150–200 mL/min for 2.5 minutes.

Due to the new SACP technique, cerebral perfusion parameters were also determined during circulatory arrest and during anastomosis formation (Table 2).

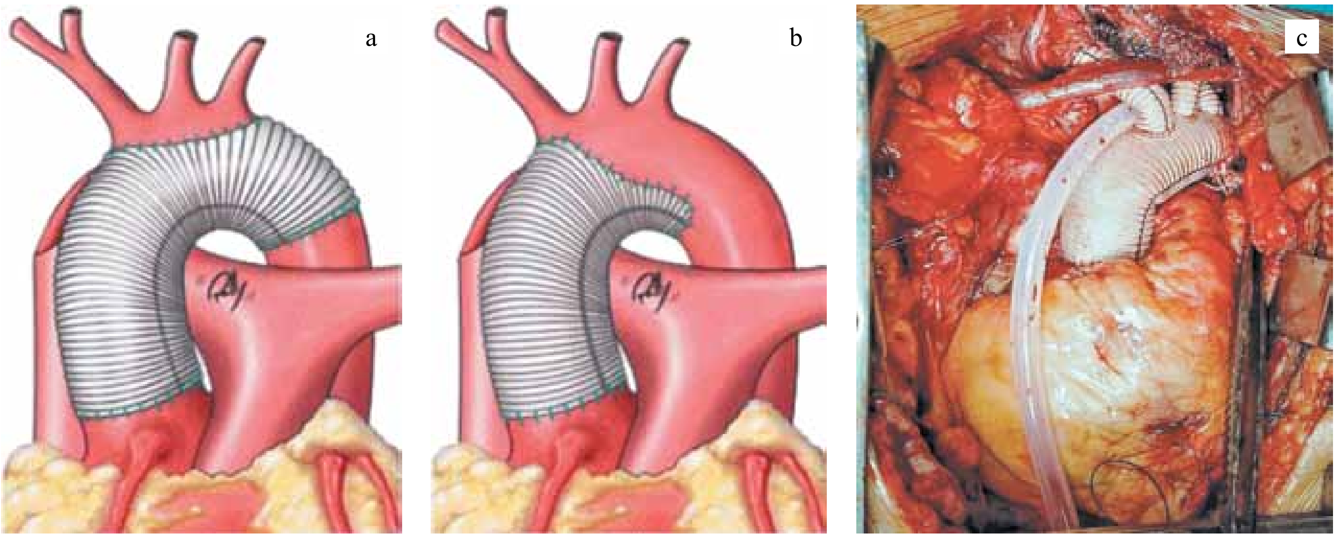

Fig. 5. Types of surgical interventions. a, prosthetic replacement of the ascending aorta and aortic arch (https://www.researchgate.net/figure/230826243_fig1_Figure-3-Supracommissural-replacement-of-the-ascending-aorta-b-hemiarch-replacement-c); b, supracoronary ascending aortic and hemiarch replacement (https://www.researchgate.net/figure/230826243_fig1_Figure-3-Supracommissural-replacement-of-the-ascending-aorta-b-hemiarch-replacement-c); c, supracoronary ascending aortic and aortic arch replacement with a multi-branch prosthesis by lowering the synthetic prosthesis into the descending thoracic aorta according to Hans Borst's elephant trunk procedure

Table 2 shows perfusion rate and resistance values in the BCA and LCCA. These characteristics allowed to exert control throughout the cerebral perfusion, as well as to regulate the flow in each hemisphere separately (using NONIN Sen Smart cerebral oximeter), which in turn increased the possibility of preventing hypoperfusion and hyperperfusion episodes.

Optimal perfusion rates and resistance values in BCA and LCCA throughout the period from cannulation to anastomosis indicate a well-performed brain perfusion. Cerebral oximetry ($SctO_2$), performed with a NONIN Sen Smart oximeter, averaged 68 ± 4.3% on the right and 66 ± 6.2% on the left, which also reflects the effectiveness of the applied perfusion technique. The mean values of cranial oximetry during the entire operation were within 63–72%.

Laboratory values presented in Tables 3 and 4 in turn suggest that there were no significant metabolic disorders during the operations.

Online monitoring of arterial and venous blood gas composition was performed during the entire period of CPB (CPI-500 device was used). Blood parameters were calibrated and monitored every 30 minutes from the beginning of CPB using laboratory diagnostics. This allowed us to maintain optimal concentrations of the main blood gas and ionic composition parameters. These indicators varied throughout the CPB period but remained within normal values due to regular monitoring and correction of metabolic disorders.

Table 1

Indicators of the selective antegrade cardioplegic perfusion conducted

Cardioplegia cannula	Flow (mL/min)	Resistance (mm Hg)
LCA, avr ± st. dev.	185 ± 14.4	100.1 ± 8.4
RCA, avr ± st. dev.	156.2 ± 21.6	106 ± 10.6

Note: LCA, left coronary artery; RCA, right coronary artery.

Table 2

Characteristics of the antegrade cerebral perfusion performed using the new technique

Perfusion cannula	Flow (mL/min)	Resistance (mm Hg)
BCA, avr ± st. dev.	165 ± 23.6	67.1 ± 16.7
LCCA, avr ± st. dev.	182 ± 12.4	70.8 ± 18.1

CONCLUSION

Based on the outcomes of our SACP technique, the clinical efficacy of this procedure has been confirmed. It allows full-scale monitoring of perfusion volume, peripheral resistance of the vascular bed in each hemisphere, controlling the level of oxygenation and independently thermoregulating the circulatory circuits of the patient's brain and body.

The presented results also show that the method is safe and potentially contributes to early activation, reduction in incidence of neurological complications, incidence of multiple organ failure and hospital mortality during interventions on the aortic arch and its branches performed under hypothermic circulatory arrest with cold cardioplegia.

Table 3

Acid-base balance parameters of arterial blood, reflecting metabolic changes during cardiopulmonary bypass (mean values are presented)

Time	HCO_3, mmol/l	pCO_2, mmHg	pO_2, mmHg	sO_2, %	Hb, g/l	Lac, mmol/l	K^+, mmol/l	Na^+, mmol/l	pH	A(BE), mmol/l	S(BE), mmol/l
5 min	24.9	32.1	263.5	99.8	91.1	1.33	4.55	117.5	7.45	0.5	0.62
30 min	23.35	28.37	224.7	99.1	91.12	1.5	4.61	132.12	7.49	–0.6	–0.42
60 min	21.31	26.53	223.96	98.8	88	2.76	5.23	131.66	7.47	–2.98	–3.58
90 min	20.3	30.22	198.8	98.6	82.08	3.9	4.02	134.8	7.40	–5.06	–4.8
120 min	21.75	31.25	210.75	99.1	86.6	3.6	3.9	136	7.42	–3.25	–3.07

Table 4

Acid-base balance parameters of venous blood, reflecting metabolic changes during cardiopulmonary bypass (mean values are presented)

Time	HCO_3, mmol/l	pCO_2, mmHg	pO_2, mmHg	sO_2, %	Hb, g/l	Lac, mmol/l	K^+, mmol/l	Na^+, mmol/l	pH	A(BE), mmol/l	S(BE), mmol/l
5 min	24.72	33.38	82.45	86.55	91.62	1.42	4.56	133.75	7.47	0.48	0.6
30 min	23.11	29.22	64.23	85.85	60.42	1.75	4.56	132.25	7.47	–1.33	–1.02
60 min	22.23	32	28.55	78.43	87.33	3.06	5.63	131.83	7.42	–2.46	–2.21
90 min	20.94	35.48	33.9	79.92	81.44	4.12	3.98	134.2	7.36	–4.32	–3.84
120 min	22.2	37.6	37.975	78.9	86.27	3.05	3.92	135.75	7.38	–2.6	–2.27

Against the background of short CPB and circulatory arrest time, sufficient perfusion, moderate hypothermia, and maintenance of target hematocrit level, the surgical outcomes look predictable and logical: a short stay in the intensive care unit, in the absence of permanent neurological deficit. No cardiac and renal complications, hospital and 30-day mortality.

Careful surgical hemostasis against the background of high-quality anesthesia allowed to minimize the number of resternotomy surgeries for bleeding to 1 case out of 10.

According to MSCT data, the radicality of the performed reconstructions on the ascending aorta and aortic arch in the postoperative period is beyond doubt. In the first days after surgery, sinus rhythm was restored in 100% of the patients with an average frequency of 79 ± 12.37 bpm. According to echo, performed on day 2 after the operation: mean diameter of the aortic valve FR did not change – 2.36 ± 0.13 cm; mean diameter of the STJ was 3.52 ± 0.15 cm; mean diameter of the ascending aorta and aortic arch was 3.18 ± 0.19 cm and 3.8 ± 0.45 cm, respectively.

The results of the immediate outcome assessment also did not reveal significant brain ischemia. This complication was detected in one patient, caused by the initial presence of cerebral ischemia zones in the patient.

The authors declare no conflict of interest.

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