IJIMM, Volume 3, Issue 1, 2025 ISSN: 2995-5319
http://medicaljournals.eu/index.php/IJIMM/issue/view/3

INTERNATIONAL JOURNAL OF
INTEGRATIVE AND
MODERN MEDICINE

History of Minimally Invasive Coronary Surgery

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Abstract: Minimally invasive surgery is an attractive choice for patients undergoing major cardiac surgery. In this article, we review the history of minimally invasive heart valve surgery. With many innovations in surgical instruments, artificial circulatory systems, imaging and robotic systems, and surgical techniques, minimally invasive cardiac surgery has become the standard treatment for valve injuries. In particular, aortic cross-clamping techniques and cardioplegia techniques using a Chitwood clamp and root cannula or endoballoon catheter combined with femoral-femoral bypass systems have made such procedures safer and more practical. On the other hand, robotic surgery has not become standard due to cost and slow learning curve. However, along with the development of robotics, this less invasive method may provide patients with another choice in the near future.

Keywords: cardiac surgery, minimally invasive surgery, valve surgery

Introduction. Aortocoronary bypass surgery (ACB) occupies an important place in the complex of modern methods of treatment of patients with coronary heart disease (CHD). In most clinics this operation is still performed under artificial circulation (AC) and cardioplegia. Less frequently, ACS is performed without AC on a working heart using OPCAB (off-pump coronary artery bypass) technology. The advantages of OPCAB over traditional ACS with PCI in patients with multifocal atherosclerosis, chronic obstructive pulmonary disease, chronic kidney disease and other severe comorbidities have been proved [1]. At the same time, in their absence in low-risk patients, refusal of PCI does not lead to significant improvement of ACS results [3, 8]. Moreover, in patients with disabled myocardium, significant dilatation and low pumping function of the left ventricle, the use of OPCAB technology is associated with an increased risk of severe hemodynamic disorders during cardiac dislocation. The optimal tactical solution in such patients can be considered ACS with PCI in auxiliary mode without cardioplegia, which excludes the mentioned central hemodynamic disorders and possible complications associated with myocardial anoxia [2].

In a number of clinics, the majority of ACS operations are performed without IC [3]. However, it should be stated that there is still a reserved attitude towards them, and the global share of such interventions among all ACS operations does not exceed 20% [3]. In our opinion, there are several reasons for this. First, there are no proven advantages of OPCAB in the above-mentioned, rather large group of low-risk patients without severe comorbidities. Secondly, excellent results of traditional ACS with IR do not always contribute to motivation for introduction of new technologies into practice [4]. Thirdly, even a great and successful experience in performing ACS with PCI and cardioplegia does not guarantee success in the adoption of OPCAB technology, which also negatively affects the attitude of many cardiac surgeons to this operation [5]. In this regard, it is necessary to mention the large randomized multicenter studies ROOBY and DOORS, in which the authors showed significantly worse patency of autovenous shunts after OPCAB compared with traditional ACS, with the same patency of mammary-coronary anastomoses and no significant differences in the incidence of adverse cardiac and cerebrovascular events within a year after surgery [6]. However, their opponents quite reasonably pointed out a significant disadvantage of these studies, which consisted in a small experience of OPCAB operations in many surgeons, resulting in a high rate of conversion to PCI (12.4%), which could not but negatively affect the presented results [7]. On the contrary, the experience of regular performance of a large number of operations without IR, when their share exceeds 60% of all ACS operations, is realized in the high quality of anastomoses formed, which is positively reflected in the results obtained. The authors of such publications , in particular, a large randomized study JOCRI (Japanese Off-Pump Coronary Investigation), found no reliable differences both in the patency of autovenous, radial and mammary-coronary shunts, and in the clinical condition of patients within 2 years after ACS under ACI and without it. This is confirmed by J. Puskas et al. [6], who in the course of a randomized study did not obtain a significant difference between OPCAB and ACS with IR in shunt patency and frequency of adverse cardiac and cerebrovascular events both in the nearest terms and 8 years after the operation.

Obviously, OPCAB can be considered as the operation of choice for high-risk patients in the hands of experienced surgeons who perform it regularly and qualitatively. Under this condition, the refusal of PCI does not affect the shunt patency in the postoperative period, and the long-term results of OPCAB are not inferior to those after traditional ACS with PCI. This approach allows to significantly expand the possibilities of OPCAB technology and use it in the majority of operated patients, if the surgeon prefers to perform myocardial revascularization without PCI.

The most important trend of modern cardiac surgery is the striving for minimal surgical trauma and the fastest possible rehabilitation of the patient, which is largely promoted by the introduction of new, increasingly advanced minimally invasive surgical technologies into the clinic [7]. In accordance with the decisions of the I World Congress on Minimally Invasive Heart Surgery, the main goal of minimally invasive myocardial revascularization is to reduce the number of complications and accelerate the patient's recovery while maintaining the effectiveness and duration of the therapeutic effect of surgery [12].

One of the main principles of such surgery is to minimize the area of intervention. The use of mini-accesses in cardiac surgery is very relevant, given the traumatic nature of sternotomy and specific complications associated with it. Even in the absence of the latter, many patients report a decrease in the quality of life for several months after surgery due to some discomfort in the sternotomy area [8]. However, it is not quite correct to consider only the small size of the surgical access as a determining factor reducing surgical trauma. A number of cardiac surgeons consider the exclusion of IC from the means of operation support as an equally important criterion of “small invasiveness”. In their opinion, refusal of IC and cardioplegia reduces the risk of intervention to a greater extent than reduction of the surgical access size [1].

OPCAB is an operation without IR through a traditional, longitudinal sternotomy. Can it be considered minimally invasive? Apparently, no, because this operation does not fully meet all the above criteria. According to A. Calafiore [9], the term “mini-invasive myocardial revascularization” should be understood only as those coronary bypass operations that are performed without sternotomy and I.C. If we are guided by this definition, there is every reason to consider V.I. Kolesov, who in 1964 was the first to perform the operation of mammary-coronary anastomosis through a left-sided thoracotomy, as the pioneer of this direction in coronary surgery. In 1971, his son E.V. Kolesov [10] summarized and presented the results of 271 such operations. Abroad, coronary artery bypass grafting using the internal thoracic artery (ICA) without IC through left-sided thoracotomy was most widespread in Argentina, where high surgical activity was characterized by F. Benetti , who in 1991 reported the results of 700 such operations. Since 1994, modern minimally invasive coronary surgery began, when F. Benetti et al. [2], as well as V. Subramanian et al. almost simultaneously presented the results of mammary-coronary bypass without IC through an antegrade mini-thoracotomy. After 2 years, excellent results of such operation in 115 patients with hospital mortality of 0.6% were demonstrated by a group of Italian cardiac surgeons headed by A. Calafiore [8]. By this time, some progress was achieved in technical support of myocardial revascularization on the working heart, the first mechanical systems of local myocardial stabilization appeared, which provided a fixed field at the site of coronary anastomosis formation [9]. In 1996, the name MIDCAB (Minimally Invasive Direct Coronary Artery Bypass) was assigned to the operation, under which it still exists today. In Russia it became widespread in 1997-1998. The pioneers and active initiators of MIDCAB implementation in the clinic were Y.V. Belov and G.P. Vlasov [1, 2]. Another solution that seemed innovative was the thoracoscopic left VGA (LVGA) dissection. This procedure eliminated the excessive traction of the ribs during direct LVGA isolation with the imperfect and traumatic retractors of the time. The use of video-assisted MIDCAB was first reported by F. Benetti et al. in 1994, and in Russia - by G.M. Soloviev et al. in 1997. [13].

While undoubtedly conforming to the above principles of minimally invasive myocardial revascularization, MIDCAB was not devoid of very significant drawbacks. First, the volume of revascularization was limited to one anterior descending artery (ADA), rarely two coronary arteries, including its diagonal branch (DV). As a result, the indications for MIDCAB arose when intervention on the PDA alone was necessary. Very soon the achieved high level of X-ray endovascular surgery allowed the majority of patients with this lesion to effectively perform coronary angioplasty with implantation of drug-eluting intracoronary stents. Therefore, the indications for MIDCAB are currently limited to situations when coronary angioplasty cannot be performed for any reason. Secondly, mini-thoracotomy does not allow for immediate IR connection in cases of emergency conversion. If this disadvantage of MIDCAB can be eliminated due to the experience of peripheral IR application, the first one was the main reason for the significant decrease of interest in this operation. In the following years, the above-mentioned OPCAB technology became incomparably more widespread. Introduction of vacuum positioning and local myocardial stabilization systems into surgical practice expanded the possibilities of this technology and allowed to perform multiple ACS without IR in patients with multivessel coronary lesions and stenosis of the left coronary artery trunk, which together constitute the vast majority of operated CHD patients [11]. However, for all its advantages, OPCAB cannot be considered a minimally invasive intervention. All sorts of problems associated with complete sternotomy remain. There are no differences from traditional ACS in the conditions of IR [8]. This circumstance was of great importance in preserving the motivation of cardiac surgeons to search for new technologies, which unlike OPCAB could fully meet the definition of “mini-invasive myocardial revascularization” and unlike MIDCAB could be applied in the majority of operated patients with different volume of coronary lesions. Now we can state that further development of minimally invasive myocardial revascularization follows several directions. The first, the most widespread is hybrid myocardial revascularization (HCR, Hybrid Coronary Revascularization), which combines the advantages of MIDCAB and percutaneous coronary intervention. HCR was initially considered as a treatment option capable of providing adequate myocardial revascularization in high-risk patients. Acceptable results promoted its further introduction into the clinic, and now HCR is included in the majority of modern recommendations for the treatment of CHD patients [10]. In particular, this technology is indicated for use in severe atherocalcinosis of the ascending aorta, “poor” condition of the target coronary arteries, conduit deficiency, PDA lesions unfavorable for stenting with a low SYNTAX score.

There are 3 options for performing HCR, each with its own advantages and disadvantages. The first option of intervention is possible in a hybrid operating room, where MIDCAB is performed first and then immediately intracoronary stenting is performed. The positive aspects of this option are the initial restoration of blood flow in the PNA and subsequent angiographic quality control of the mammary-coronary anastomosis; the negative aspects are the high risk of bleeding due to the need to start disaggregant therapy immediately after heparin neutralization, as well as the risk of contrast-induced nephropathy on the background of surgical stress. All of the above requires coordinated, highly professional work of cardiac surgeons, anesthesiologists and interventional cardiologists. The second option is delayed intracoronary stenting for several days after MIDCAB, which does not require a hybrid operating room. Previously restored blood flow in the PNA allows in such situations to safely perform angioplasty for left coronary artery (LCA) trunk lesions and envelope artery (EA) mouth lesions, there is a possibility of angiographic quality control of the mammary-coronary anastomosis. There is no high risk of bleeding, but the patient undergoes two interventions, with a risk of unrevascularized myocardial ischemia during the angioplasty waiting period. The third option of hybrid intervention with initial coronary angioplasty and delayed MIDCAB is rarely performed, mainly in cases of acute coronary syndrome and the need for intracoronary stenting of infarct-responsive OA or right coronary artery (RCA). A hybrid operating room is not required in these situations. In addition, there is a risk of thrombosis of previously implanted stents with temporary interruption of disaggregant therapy and heparin neutralization after MIDCAB [7].

In general, a number of researchers [1] indicate certain advantages of HCR over multiple coronary artery bypass grafting in a certain, carefully selected group of high-risk patients with low SYNTAX score. In the hospital phase of treatment, these advantages include a reduction in the duration of artificial ventilation (AV) and time in the cardiac intensive care unit, reduced need for transfusion of blood components, and shorter hospitalization time. However, there are no differences in hospital mortality, incidence of adverse cardiovascular events in the 1st year after HCR. Further the need for repeated myocardial revascularization is significantly higher after hybrid intervention.

The most high-tech method of minimally invasive myocardial revascularization is robot-assisted, totally endoscopic coronary artery bypass (TECAB - Total Endoscopic Coronary Artery Bypass). Over the 20 years of its development since the experimental work of E. Stephenson and C. Ducko, the first TECAB operation in the world, successfully performed by D. Loulmet in Paris. Loulmet at the Paris clinic in 1998, coronary robotic surgery has made impressive progress [5]. Currently, it is concentrated in a number of cardiac surgery centers in the USA, Canada, Germany, and Southeast Asian countries. Initially, the use of robotic systems Zeus and then the first generations of da Vinci was limited to the isolation of the VGA and the formation of mammary-coronary anastomosis between the LVGA and the PNA. Surgical access to other target coronary arteries was performed via longitudinal sternotomy and much less frequently via left anterior mini-thoracotomy [6]. In 2000. U. Kappert et al. [4] from Dresden reported for the first time a successful operation of fully endoscopic bilateral mammary-coronary bypass in which the LVGA was used for the blunt edge branch of the OA and the right VGA for the PNA. It is quite natural that at the initial stage of its development robot-assisted coronary artery bypass grafting was often accompanied by intraoperative complications, the incidence of which was up to 50%. The problems concerned both the isolation of VGAs and the formation of distal anastomoses. Such complications often led to conversion to conventional ACS, were accompanied by an increase in the operation time, ventilatory support, cardiac intensive care and hospital stay, but, fortunately, did not lead to an increase in hospital mortality [5]. As experience was accumulated, there was a clear trend toward significantly lower complication rates, and TECAB became increasingly competitive with traditional ACS. The advantages of TECAB were shorter duration of hospitalization, rapid physical rehabilitation, and less pain in the first months after surgery [3]. S. Savista et al. [4] in 2010 presented the results of TECAB of 1, 2 and 3 coronary arteries performed between 2004 and 2007. In addition to excellent immediate and long-term results, the authors reported excellent shunt patency of 98.6%.

Modern TECAB is a multiple bimammary coronary bypass surgery performed with complete preservation of the integrity of the chest without any surgical access. The volume of myocardial revascularization ranges from 1 to 4 coronary arteries [4]. With a preserved chest, the length of two in situ CAA is usually sufficient to create the required number of coronary anastomoses. CAA is isolated skeletonized [7]. In most patients, operations are performed under peripheral IR conditions with transfemoral cannulation. Cardioplegia is performed through an endoaortic balloon catheter, which is inserted through a lateral branch of the arterial highway. Under the control of transesophageal echocardiography, a catheter is inserted into the ascending aorta, a balloon is inflated, the aorta is completely obstructed and, as a rule, blood cardioplegia is performed [5]. TECAB is no less common on a working heart in conditions of parallel IC, which is advisable to use in patients with low functional reserves of the myocardium [14]. Operations without IC are performed relatively rarely, due to the high risk of disorders of central hemodynamics with dislocation of the heart inside the closed chest cavity. Until recently, the exception was isolated mammary coronary artery bypass grafting [9]. However, there is currently a trend towards an increase in the number of operations of robot-assisted multiple coronary bypass surgery without IR. It should be noted that TECAB can be both an independent method of surgical treatment and a component of HCR, thereby enhancing its minimally invasive nature [6].

Despite all the obvious advantages, TECAB technology has not yet found wide application in cardiac surgery practice, primarily due to its high cost. Many clinics cannot afford to purchase and operate modern robotic systems for financial reasons. In addition, the long learning curve of TECAB indicates a more complex and lengthy process of achieving the necessary qualifications compared to other methods of myocardial revascularization [3]. Therefore, this technology, despite the gradual expansion of its geography, still remains the prerogative of a small number of specialized and high-budget centers [9]. The above disadvantages are largely devoid of another direction of minimally invasive myocardial revascularization, focused on performing multiple coronary bypass surgery through left anterolateral mini-thoracotomy (MICS CABG — Minimally Invasive Cardiac Surgery/Coronary Artery Bypass Grafting). The first such operation without IR was performed by J. McGinn et al. [6] in January 2005 in New York at the Heart Institute. By 2014, more than 1,000 surgical procedures had been performed using this technology. The operation has spread to a number of clinics in the USA and Canada, Europe, Japan, India and China [19]. In Russia, MICS CABG is performed in cardiac surgery clinics in Astrakhan, St. Petersburg and Moscow [9].

All stages of the operation are performed by the surgeon under direct visual control without video consistency. There is no need for an expensive robotic system and consumables. MICS CABG technology differs from MIDCAB in the ability to perform multiple bypass surgery in patients with multivessel coronary artery disease. In this respect, the operation is similar to traditional CABG via median sternotomy [10]. However, unlike it, MICS CABG is accompanied by minimal surgical trauma and complete preservation of the chest frame, rapid rehabilitation and excellent cosmetic effect. Due to this, the time spent by patients in the intensive care unit, the duration of hospitalization after surgery (on average 4 days) are reduced, the risk of sternal infection and the need to interrupt even double disaggregant therapy are completely absent [11]. Complete myocardial revascularization can be performed in 95% of patients operated on using this technology. The perioperative mortality rate does not exceed 1.3%. In addition, there is no doubt that there is a decrease in the need for hemotransfusion, as well as an early return of patients to full physical and social activity [18]. Summing up 10 years of experience in performing MICS CABG, J. McGinn et al. [9] highly appreciated its clinical efficacy. In the period up to 8 years after surgery (on average for 2.9±2.0 years), the survival rate was 96%, the frequency of adverse cardiac and cerebrovascular events was 2%, the need for repeated myocardial revascularization was 7%, while the frequency of repeated interventions on previously shunted coronary arteries was 1%. Such a significant clinical result of the operation, which is not inferior to traditional CABG, is explained by the high functional viability of shunts after MICS CABG. Their total patency six months after surgery is 92% with absolute (100%) patency of the VA shunts [17]. High-quality anastomosis is an indispensable condition for achieving such indicators. In addition to the necessary experience and surgical skill, the full implementation of this condition depends on the exposure and visualization of the target coronary arteries. In this regard, it should be noted that mini-thoracotomy is usually performed more laterally compared to MIDCAB surgery. This access allows the ribs to be spread wider with less risk of damage and to ensure optimal exposure not only of the PA, but also of the branches of the OA and the PA [16]. Isolation of both CAA, as well as the formation of proximal anastomoses on the ascending aorta, significantly facilitate single–lung ventilation of the right lung - an obligatory element of the anesthesiological aid for MICS CABG [4]. Then, two CAA can be used both in situ and in composite structures for multiple bimammary coronary bypass surgery, eliminating manipulations on the aorta. In addition, some surgeons suggest thoracoscopic CAA isolation, which reduces the size of a mini-thoracotomy and eliminates excessive intercostal traction, which is possible with the mobilization of CAA under direct visual control [15].

In accordance with one of the fundamental principles of minimally invasive cardiac surgery, MICS CABG surgery is performed, as a rule, without I.K. However, sometimes with a large volume of revascularization, a reduced fraction of the expulsion of the left ventricle, the use of IR in an auxiliary mode is justified, for which its peripheral connection is used through cannulation of the femoral vessels [10]. This technique is optimal for calm work with complex patients, which is extremely important for gaining the necessary experience of such operations. In addition, the operation can be performed under conditions of complete IR and cardioplegia. The cardioplegic solution is supplied through a catheter integrated into the arterial trunk of the IC contour, a balloon is fixed on it, the inflating of which leads to obturation of the ascending aorta. Compression of the aorta can also be performed externally with a clamp connected to it through an additional port, with infusion of cardioplegic solution into the ascending aorta.

With all the undoubted advantages, MICS CABG technology still has certain limitations. However, only some of them can be considered contraindications to its use. Most of the others, as a rule, are due to insufficient experience of such operations and can be leveled as it accumulates. The first should include low tolerance to single-lung ventilation, which is usually found in severe chronic obstructive pulmonary disease [13]. The degree of its severity can be judged by the Tiffno index — the ratio of the volume of forced exhalation in 1 s (OFV1) to the forced vital capacity of the lungs (FVC). Its decrease of less than 0.5 indicates severe bronchial obstruction and an extremely high risk of single-lung ventilation. MICS CABG is not indicated for patients who have previously undergone surgery with invasion of the left pleural cavity. In addition, surgery is contraindicated in cases of significant atherosclerotic lesion of the arteries of the lower extremities, which excludes the possibility of safely connecting the peripheral I.K. Great caution should be exercised when using this technology in patients with disabled myocardium and cardiomegaly, when the risk of hemodynamic disorders increases significantly when positioning the heart. It is safer for such patients to perform surgery in conditions of parallel IC with its transfemoral or central connection, abandoning the mini-access in favor of traditional sternotomy in the latter case.

At the stage of mastering MICS CABG, certain limitations may be associated with its technical performance in some groups of patients. Possible difficulties in exposing the surgical field through mini-thoracotomy in overweight patients dictate the need to accumulate initial experience of this operation in normosthenic patients with wide intercostal spaces. The anatomical conditions in such cases are close to ideal, providing optimal visualization of the target coronary arteries. Objective difficulties in the formation of distal anastomoses with diffuse coronary artery disease, and the frequent need for endarterectomy in traditional CABG can become a serious obstacle to the success of the first MICS CABG operations. On the contrary, a multivessel, but local lesion with a sufficient diameter of the target coronary arteries and a good condition of their distal bed will undoubtedly contribute to this success. However, the above difficulties cannot be considered contraindications to MICS CABG, because with sufficient experience and high qualification of the surgeon, they do not interfere with the performance of these operations.

Methodology

This article reviews the evolution and advancements in minimally invasive coronary surgery, specifically focusing on aortic coronary bypass (ACB) and off-pump coronary artery bypass (OPCAB) procedures. A literature review was conducted to examine historical developments, including key technological innovations such as artificial circulatory systems, imaging systems, and robotic surgery. The review also analyzes clinical studies, including randomized trials, that compare OPCAB and traditional ACB techniques. Additionally, the article explores the development of hybrid coronary revascularization (HCR) techniques, combining MIDCAB with percutaneous coronary intervention (PCI), and assesses their impact on treatment outcomes. Data from various multicenter studies and clinical reports were synthesized to evaluate the effectiveness, safety, and limitations of these minimally invasive procedures.

Results and Discussion

Minimally invasive coronary surgery techniques, such as OPCAB, have shown favorable results in reducing surgical trauma and enhancing recovery times compared to traditional methods. OPCAB offers similar outcomes to standard bypass surgery in low-risk patients, with comparable graft patency and fewer complications. Hybrid coronary revascularization (HCR) combining MIDCAB and PCI has also demonstrated positive results, particularly for complex coronary conditions, though it requires coordinated care and carries risks like bleeding and contrast-induced nephropathy. Despite the potential of robotic surgery, its widespread use remains limited due to cost and a slow learning curve.

Overall, minimally invasive approaches offer promising alternatives, but further refinement and experience are needed to optimize their application in a broader patient population.

Conclusions: Thus, the current trend towards minimizing surgical trauma has been developed in the surgery of coronary heart disease in several directions at once. The possibility of performing hybrid myocardial revascularization (HCR) should first of all be considered with a high risk of multiple coronary bypass surgery, a deficiency of conduits, a lesion unfavorable for stenting with a low SYNTAX score, pronounced atherocalcinosis of the ascending aorta without the chance of using the surgical technique "no-touch aorta". Robot-assisted, fully endoscopic coronary bypass surgery (TECAB) allows for complete myocardial revascularization without access at all, minimizing surgical trauma to the patient. Undoubtedly, the most advanced TECAB technologies ensure the maximum realization of the surgeon's professional skill in achieving the desired result of the operation with minimal trauma to the patient. However, the high cost, long and rather difficult training period are factors that still hinder the introduction of this technology into a wide range of cardiac surgery practice. Unlike TECAB, the MICS CABG operation does not involve such significant material costs, the learning curve indicates its high reproducibility. As a rule, the experience of OPCAB operations allows you to quickly master this technology [70]. With the accumulation of experience in its application, the indications for it can be significantly expanded. Therefore, in the near future, MICS CABG surgery can be considered as one of the main methods of minimally invasive myocardial revascularization.

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