Asia Pacific Academy of Science Pte. Ltd.

Cardiac and Cardiovascular Research 2024, 5(2), 2947.
https://doi.org/10.54517/ccr.v5i2.2947

Review

Robot-assisted coronary surgery: A narrative review on the available data

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CITATION

D’Auria F, Santo DF. Robot-assisted coronary surgery: A narrative review on the available data. Cardiac and Cardiovascular Research. 2024; 5(2): 2947.
https://doi.org/10.54517/ccr.v5i2.2947

ARTICLE INFO

Received: 18 September 2024
Accepted: 29 November 2024
Available online: 26 December 2024

Abstract: The robot-based approach has been the most significant advancement in minimally invasive surgery over the past decade. Robotic coronary heart surgery represents half of the total cases of robotics-based cardiac surgery. Since 1998, it has emerged as a revolutionary approach to standard coronary surgery. However, despite its promising beginning, there has been a growing interest in the application of robotics in surgical fields other than cardiac surgery, such as urology and general surgery. In various waves of enthusiasm, single pioneers or visionary cardiac surgeons have tried to extend robotic surgery to different heart procedures, but they still struggled to practice it as a routine approach. Over the last 20 years, robotic platforms have gained importance in minimally invasive heart surgery, with proven safety and efficacy. However, despite its feasibility, safety, and efficacy, less than 0.5%–1.0% of coronary artery bypass grafting procedures are performed using a robot-assisted setup. We believe that in cardiac surgery, the time is ripe to open up new surgical strategies that are increasingly devoted to robotics, hybrid, and augmented-reality-based assistance. With this in mind, we wish to propose an excursus on the state of the art of coronary robotic surgery, its promising results, and its possible future perspectives, with a focus on the most recent achievements. This narrative minireview addresses, therefore, experiences and all aspects related to such a technique, with particular attention gained in robotic coronary revascularization, to the anaesthesiologic as well as surgical aspects, on the learning curve, patient outcome, and related costs, wishing to enlarge the portfolio of the younger generation of cardiac surgeons. In effect, according to the literature data, we are confident that robotic heart surgery is burgeoning, and the new generation of cardiac surgeons must face a gorgeous future if we invest in training and technology.

Keywords: MIDCAB; TECAB; ThoraCAB; robotic coronary surgery; robotic cardiac surgery; OPCABG; CABG; hybrid coronary surgery; hybrid coronary revascularizaiton; da Vinci Surgical System; minimally invasive revascularization

1. Introduction

In a World where technique and technology have a supersonic evolution in each field of human activities and artificial intelligence (AI) has become a daily element in actual and future human activities, it seems strange that robotic cardiac surgery is struggling to spread, preventing the full evaluation of its efficacy and benefits because of the lack of wide and systematic operating cases worldwide. The lack of a surgeon’s stimulus to technological innovation and the complete change of technical perspective and conception in each kind of cardiac operation makes the industry uninterested in robotic investment in cardiac surgery. This aspect greatly slows down the change and evolution of our surgery, depriving our patients of the benefits that technological innovation brings with it. We believe that in cardiac surgery, the time is now ripe to open up new surgical approaches that are increasingly devoted to robotics, hybrid, and augmented-reality-based surgery [1,2]. With this in mind, we wish to propose an excursus on the state-of-the-art of robot-assisted coronary surgery and its possible future perspectives. Despite we prefer to propose a narrative review on robot-assisted coronary surgery, the literature review was performed according to the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines as it is the most complete and exhaustive method for article selection.

1.1. Brief history of robotic surgery developments

The first surgical robot in the World was Arthrobot. It appeared in 1983 and was designed to aid orthopaedic procedures. In 1985, PUMA 560 (Unimate, Mercer County, NJ, US) was introduced to perform CT-scan-guided brain biopsies. This model was followed in 1988 by ROBODOC (Integrated Surgical Systems, Davis, DE, US), a system that was applied to total hip arthroplasty; it allowed precise preoperative planning and mill out punctual fittings in the femur for hip replacement. The first robotic application in urology occurred in 1988 at Imperial College (London, UK) with the use of PROBOT in clinical trials for transurethral surgery. In 1993, Computer Motion, Inc (Santa Barbara, CA, US), the original leading medical robot supplier, released AESOP (Automated Endoscopic System for Optimal Positioning), a robotic arm to assist in laparoscopic camera holding and positioning. The Cyber-Knife (Accuray, Sunnyvale, CA, US) was introduced in 1994 for stereotactic radiosurgery in neurosurgery. The year 1998 was a significant milestone as the ZEUS Robotic Surgical System (Computer Motion, Inc.) and da Vinci Surgical System (Intuitive Surgical, Inc., Sunnyvale, CA, US) were launched on the market. Both systems are comprised of a surgical control center and robotic arms. The first da Vinci robotic surgical procedure was a robot-assisted heart bypass, which took place in Paris in 1998 [3]. In 2000, the da Vinci robot was approved by the US Food and Drug Administration (FDA) for use in laparoscopic procedures. The first robot-assisted radical prostatectomy (RARP) was performed in Paris in the same year [4]. Intuitive Surgical, Inc. took over Computer Motion, Inc. in 2003 and is now the sole company which trades robotic surgical devices for the Western world. Other companies, such as Olympus and Samsung, are developing new robotic surgical systems, with the promise of lower cost and more compact machines. Despite the relentless evolution of robot-assisted cardiac surgery since the 1990s, the first coronary and mitral valve procedure [3], there was no widespread diffusion of the technique, and cardiac surgery uses the technical comfort that is developed for other surgeries such as urology and general surgery, without being able to express cardiac surgery-specific needs in robotic procedures, and consequently, without finding specific solutions.

1.2. Robot-assisted cardiac surgery

The da Vinci Surgical System (Intuitive Surgical, Inc., Sunnyvale, CA, USA) is the most commonly used robot in cardiac surgery. It currently has three versions on the market, da Vinci Si, da Vinci X, da Vinci Xi, and da Vinci 5, which is designed to enable better outcomes, more efficiency, and actionable insights, da Vinci 5 brings more than 150 design innovations and 10,000x the computing power of da Vinci Xi.1. These advances support enhanced surgical senses, greater surgeon autonomy, more streamlined operating rooms workflows, and advanced data analytics to improve the future of surgery. Because of the significant advantages of robotic surgery, for example, in the US, there was a 75% increase in the purchase of robotic systems between 2007 and 2009, and in accordance with this data, there was a six-fold increase in robotic cardiac procedures over the same timeframe. Yanagawa et al. [5] in 2015, analysed the critical outcomes of 5199 patients who underwent robot-assisted cardiac surgery compared to a propensity-matched population who underwent traditional operations and found that the robot cluster had fewer overall perioperative complications, shorter length of in-hospital stays, and lower long-term mortality rate. Shain et al. [6] in 2018 reported 4271 robot-assisted thoracic operations up to 30 September 2017, with enthusiasm towards the training investments that these techniques deserve to receive worldwide, as was previously reported by Cerfolio et co-workers [7] in 2016. Half of the robotic cardiac operations performed worldwide involve coronary artery bypass grafting (CABG) [8]. However, the da Vinci Surgical Systems also allows mitral valve repair and replacement surgery, tricuspid valve surgery [9], ablation for atrial fibrillation [10,11], left atrial appendage occlusion [12,13], atrial septal defect repair [14], anomalous pulmonary venous return or congenital atrio-ventricular canal defect [15–19], ventricular septal defect [20], and intracardiac masses abscissions [21]. Aortic valve fibroelastoma removal [22,23] and sporadic cases of aortic valve replacement [24–26] have also been described in the literature as pioneer cases of robot-assisted endoscopic thoracic aortic anastomosis in juvenile lamps [27].

2. Material and methods

Despite we prefer to propose a narrative review on robot-assisted coronary surgery, the literature review was performed according to the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines. Literature search and data extraction for eligible studies were performed by consulting the Cochrane Central Register of Controlled Trials (CENTRAL Internet), MEDLINE, and EMBASE, without date or language restrictions. Keywords and Medical Subject Headings terms pertinent to the exposure of interest were used in relevant combinations: MIDCAB, TECAB, ThoraCAB, robotic coronary surgery, robotic cardiac surgery, OPCABG, CABG, hybrid coronary surgery, hybrid coronary revascularization, da Vinci Surgical System, and minimally invasive revascularization. A literature search was conducted from January 1983 to October 2024. In addition, we searched trial registries, and the reference lists were carefully analysed for pertinent studies. Randomized controlled trials (RCTs) and prospective and retrospective observational cohort studies of adult TECAB and MIDCAB were included in our review. Studies that met one of the following exclusion criteria were excluded from the analysis: Case reports, animal and in vitro experiments, conference abstracts, incomplete information about study objectives, and studies in which outcomes were expressed as continuous variables. Supplementary documents of the selected studies were also assessed, if available. Two investigators (FDA and DFS) independently screened the titles and abstracts and resolved any disagreements. After excluding non-relevant studies, the full texts of potentially relevant articles were screened for inclusion in the final narrative review.

3. Results

3.1. Robot-assisted coronary surgery

The wording *Robot-Assisted Coronary Surgery* includes two different surgical procedures, with different indications and technical features: *Robotic Minimally Invasive Direct Coronary Artery Bypass (MIDCAB)* and *Robotic Total Endoscopic Coronary Artery Bypass (TECAB)*, as schematized in **Figure 1**. In 2003, Srivastava et al. [28] coined the term *ThoraCAB* to refer to MIDCAB with robot-assisted internal thoracic artery harvesting. However, we commonly define this procedure as robot-assisted MIDCAB. To date, Robotic Minimally Invasive Direct Coronary Artery Bypass (MIDCAB) has been the most common procedure in cardiac surgery. This surgical procedure consists of robotic left internal mammary artery (LIMA) harvesting followed by a small left mini-thoracotomy through which a traditional open off-pump coronary anastomosis is performed on the left anterior descending artery (LAD). MIDCAB is useful for treating single-vessel disease (LAD) or multiple-vessel disease through hybrid coronary revascularization (HCR) in association with a percutaneous coronary intervention (PCI) procedure. In 2018, ESC/EACTS guidelines on myocardial revascularization indicated the hybrid procedure (IIb B) when multi-vessels CABGs are risky and/or PCIs are unsuitable. In contrast, they presented a level of evidence of IB for minimally invasive revascularization in cases of atherosclerotic aortic disease because of the no-touch technique. Minimally invasive coronary surgery with LIMA harvested either directly or under video-assisted vision may represent an attractive alternative to sternotomy. It has a similar safety and efficacy profile to conventional on-pump and off-pump procedures, with a markedly reduced postoperative length of stay and an early quality of life benefit, although rib spreading is associated with increased postoperative pain. It is safe and effective in the treatment of proximal LAD stenosis or chronically occluded LAD artery. Moreover, when compared with PCI in a setting of single-vessel proximal LAD disease, minimally invasive coronary surgery was associated with a lower need for coronary reintervention. When combined with PCI for non-LAD vessels, it provides the opportunity for HCR to be performed in selected patients with multivessel disease. HCR can be consecutively performed in a hybrid operating room or on separate occasions in conventional surgical and PCI environments [29–31]. In a small randomized trial of 200 patients, the 1-year and 5-year rates of death, myocardial infarction, stroke, and major bleeding or repeat revascularization were not significantly different between HCR and CABG [32]. In 2019, Guan and colleagues [33,34] performed a meta-analysis in which they demonstrated interesting results in favor of HCR over minimally invasive coronary revascularization. In 2012, Dhawan et al. [35] retrospectively analyzed 106 patients and showed that addressing multivessel coronary artery disease using total endoscopic coronary artery bypass offers no obvious clinical benefits and might increase morbidity and mortality. In contrast, in 2014, Wang et al. [36] in their metanalysis showed that the outcomes of TECAB had reduced major adverse cardiovascular and cerebrovascular events

(MACCE) after 12 months. In addition, TECAB did not increase the rates of MACCE in the hospital, graft stenosis (or occlusion), or the need for reintervention compared with traditional CABG. In 2012, Srivastava et al. [37] and Bonatti et al. [38], as well as Bonaros et al. [39,40] in both 2013 and 2014, experienced encouraging results from TECAB. The same data were presented in 2015 by Cavallaro et al. [41], Zaouter et al. [42], in 2017 by Kofler and colleagues [43], but also in 2024 by Alaj et al. [44], Algoet et al. [45], and Weimann et al. [46], as summarized in **Table 1**. Heart Team discussions and the prospective planning of a joint strategy are critical for the success of the HCR strategy, which could be complementary to minimally invasive coronary revascularization, as stated by the AHA/ACC/STS guidelines in 2017 [29]. At this stage of experience, MIDCAB is not appropriate for unstable patients and emergency settings [30,31]. Relative contraindications are related to impaired left ventricle function and lung capacity for the toleration of single-lung ventilation with the Carlens tube [32,47], meanwhile, a discussion is ongoing about the benefit in bariatric patients, where the technique per se is more challenging and has longer operative time, but good mid-term and long-term outcomes are described in this cluster of patients, especially for the reduction in wound infection [48,49]. MIDCAB may also be very useful in patients who have undergone a previous cardiac operation, avoiding the risk of heart injury due to open re-dissection [50].

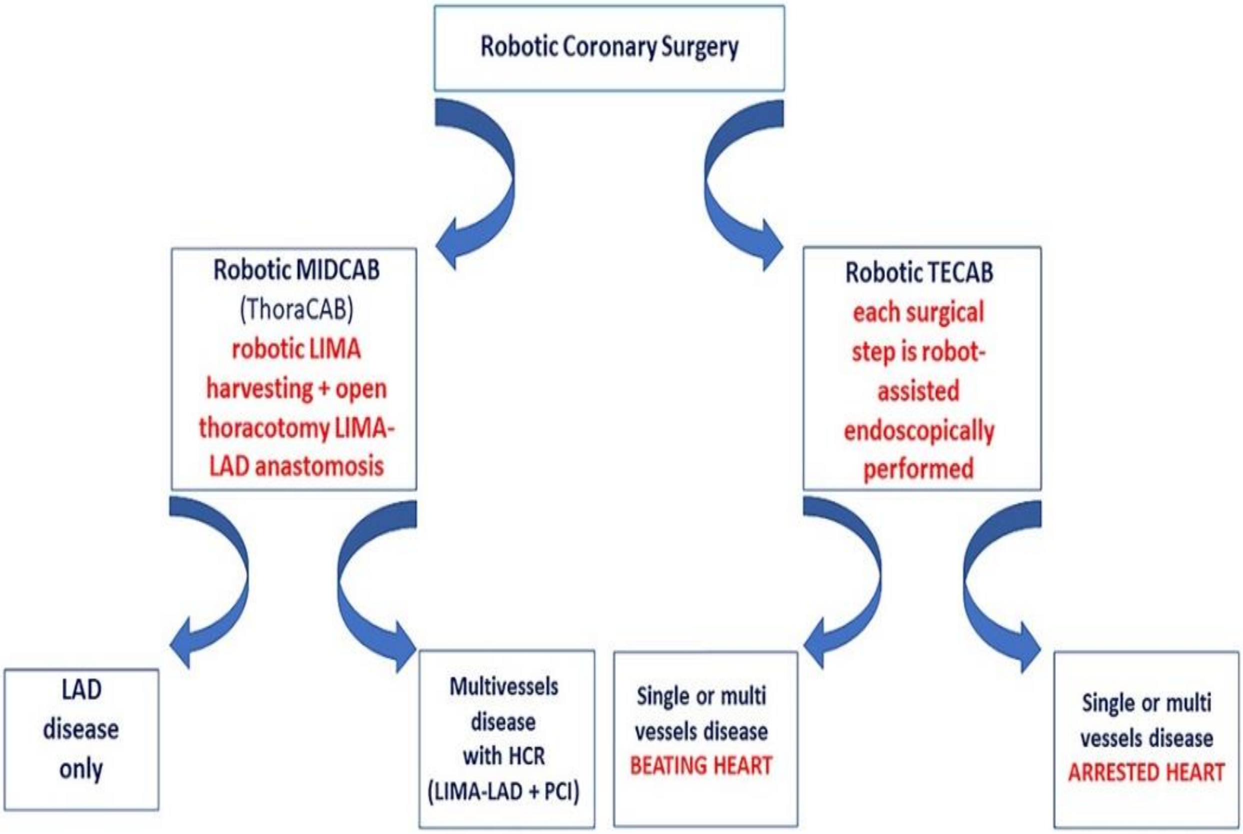

Figure 1. Schematic representation of robotic MIDCAB and robotic TECAB features.

Table 1. Summary of key studies and of the most recent studies on robotic coronary surgery with their main results.

Authors	**Year**	**Place**	**Type**	**Patients**	**Main Results**
Yusuf et al.	2024	India	Observational, retrospective	195 TECAB	TECAB is viable procedure in selected patients (30 day—mortality 1.02%).
Alaj et al.	2024	E.U.	Observational, retrospective	91 MIDCAB vs literature	Postoperative complication rate of MIDCAB lower than data reported in literature, and the short-term survival favourable.
Algoet et al.	2024	E.U.	Observational, retrospective	77 MIDCAB vs 601OPCAB propensity matched.	MIDCAB safe in terms of MACCE and mortality. Additional advantages are shorter length of hospital stay, fewer ICU admissions, and less blood transfusion.
Weymann et al.	2024	E.U.	Observational, retrospective (sixteen follow up)	301 MIDCAB	MIDCAB is a safe option with favourable survival rates, justifying its consideration in high-volume hospital which are focused on minimally invasive techniques.
Guan et al.	2019	C.P.R.	Review meta-analysis	1084 cases of HCR vs. 2349 cases of MIDCAB/TECAB	HCR was noninferior to MIDCAB/TECAB in terms of in-hospital mortality, MACCE, shock, MI, long-term survival, total variable cost, and surgical complications (including renal failure, chest drainage, bleeding), whereas HCR was associated with a reduced need for ICU LOS, hospital time, and blood transfusion than MIDCAB/TECAB and less infection than MIDCAB/TECAB. Further randomized studies are warranted to corroborate these observational data.
Balkhy et al.	2019	U.S.	Observational, retrospective	16 TECAB right coronary artery	Robotic beating-heart TECAB for isolated RCA disease is a feasible operation in selected patients. This technique is possible even for the posterior descending artery.
Gobolos et al.	2019	U.A.E.	Review meta-analysis	2397 TECAB	TECAB remains the surgical revascularization method with the least tissue trauma and represents an opportunity for coronary artery bypass grafting via port access. Rates of major complications are at least similar to conventional surgical access procedures.
Leonard et al.	2018	U.S.–U.K.	Meta-analysis	17 single-arm TECAB articles	TECAB has an acceptably low operative risk and a good early patency rate. The incidence of perioperative MI requires further investigation. The dearth of data comparing TECAB to open approaches compels the need for future comparative trials.
Kofler et al.	2017	U.S.–U.A.E.	Observational, retrospective	204 arrested heart TECAB vs 60 MIDCAB	Robotically assisted arrested heart TECAB and robotic MIDCAB perform equally in terms of perioperative results and mid-term follow-up in this single-center patient cohort.
Whellan et al.	2016	U.S.	Observational, retrospective	Trends per year of robotic procedures.	RA-CABG patients had significantly lower unadjusted major complication rates (10.2% vs 13.5%, $p < 0.0001$), including postoperative renal failure (2.2% vs 2.9%, $p < 0.0001$), and shorter length of stay (4 vs 5 days, $p < 0.0001$). The difference in operative death was not significant (odds ratio, 1.10; 95% confidence interval, 0.92 to 1.30, $p = 0.29$). RA-CABG use remained relatively stagnant during the analysis period despite lower rates of major perioperative complications and no difference in operative deaths. Additional analysis is needed to fully understand the role that robotic technology will play in CABG operations in the future.

Table 1. (*Continued*).

Authors	**Year**	**Place**	**Type**	**Patients**	**Main Results**
Leyvi et al.	2016	U.S.	Retrospective propensity matched.	2,808 robotic procedures (2007–2012)	Robotically assisted CABG does not increase the cost of the index hospitalization when compared to conventional CABG unless hybrid revascularization is performed on the same admission.
Cavallaro et al.	2015	U.S.	Retrospective propensity matched	2,582 robotic procedures (2008–2010)	Robotic assistance is associated with lower rates of postoperative complications in highly selected patients undergoing single coronary artery bypass surgery, but the benefits of this approach are reduced in patients who require multiple coronary artery bypass grafts.
Zaouter et al.	2015	E.U. (France and Belgium)	Observational, retrospective	38 TECAB vs. 33 standard CABG	The present results suggested that a program coupling a beating-heart TECAB with a preliminary ERAS path for patients requiring a single coronary revascularization is feasible and safe. This approach could reduce postoperative mechanical ventilation time, transfusion rate, and both intensive care unit and hospital stay.
Yanagawa et al.	2015	U.S.	Retrospective propensity matched.	5199 robotic procedures (2008–2011)	Overall, robotic-assisted surgery has significantly reduced median LOS, complications, and mortality compared with nonrobotic surgery.
Bonatti J et al.	2014	E.U. (Austria), U.S., U.A.E.	Observational, retrospective	90 TECAB + PCI (MV-TECAB + PCI, MV-PCI + TECAB, MV-TECAB + MV-PCI)	AHR yields comparable results with CHR and can be taken into consideration as a sternum-sparing technique for the treatment of MV-coronary artery disease in selected patients.
Wang et al.	2014	C.P.R.	Meta-analysis	16 TECAB articles	TECAB is safe and feasible therapies for CHD. This meta-analysis supports TECAB using the da Vinci surgical system to treat CHD with reduced MACCE after 12 months. In addition, TECAB does not increase the rates of MACCE in hospital, graft stenosis (or occlusion), and the need for reintervention compared with traditional CABG.
Bonaros et al.	2013	U.S.	Retrospective propensity matched.	500 TECAB (2001–2011)	Single-vessel and multivessel TECAB procedures can be safely performed with good reproducible results. Predictors of success include procedure simplicity and non-learning curve cases, whereas predictors of safety are mainly associated with patient selection.
Srivastava et al.	2012	U.S.	Observational, retrospective	164 TECAB (2008–2011)	Beating heart TECABG conversion rates decline with experience and thorough preoperative planning as well as with implementation of specific steps to minimize conversion.
Dhawan et al.	2012	U.S.	Observational, retrospective	106 TECAB	Results suggest that addressing multivessel coronary artery disease using total endoscopic coronary artery bypass offers no obvious clinical benefits and might increase the morbidity and mortality.
Bonatti J et al.	2012	U.S.	Observational, retrospective	226 robotic multivessels procedures + PCI (2001–2011)	Robotically assisted hybrid coronary intervention enables surgical treatment of multivessel coronary artery disease with minimal trauma. Perioperative results and intermediate-term outcomes meet the standards of open coronary artery bypass grafting. Recovery time is short, and reintervention rates are acceptable.
Srivastava et al.	2003	U.S.	Observational, retrospective	200 ThoraCAB	ThoraCAB has been feasible in the vast majority of patients requiring coronary bypass surgery. The prevalence of postoperative atrial fibrillation was low. Postoperative pain maybe lessened with intercostal nerve freezing.

3.2. MIDCAB surgical setting

The left lung is required to be deflected. Three trocars are introduced under vision in the second, fourth, and fifth/sixth intercostal spaces, 12 mmHg Carbon Dioxide insufflates the hemithorax. LIMA is harvested using robot in a skeletonized fashion. The pericardium is opened over the right ventricle outflow tract, and LAD is identified. Systemic heparinization is administered and a small left mini-thoracotomy is cut where the camera trocar was before. A soft tissue retractor is positioned to improve the exposure. LIMA-LAD anastomosis is off-pump performed under direct vision and intraoperative ultrasound graft is used to check its patency. **Figure 2** shows the MIDCAB surgical setting. MIDCAB can be routinely performed under dual antiplatelet therapy (DAPT) without a significant increase in bleeding [50]. This is important because sometimes, in the case of a non-LAD culprit lesion that is treated by PCI, we can concomitantly discover a LAD silent lesion and we can subsequently treat it by MIDCAB during DAPT. On the other hand, we can perform MIDCAB LIMA-LAD and after 4 months we can complete the revascularization by PCI in non-LAD vessels checking with angiography the previous bypass. According to the literature, the results of MIDCAB and HCR are very promising. Kon et al. [51] reported low perioperative morbidity and mortality and a good rate of graft patency in the mid and long-term follow-up. Patel et al. [52] and Sardar et al. [53] in 2018, Endo et al. [8] in 2019, and Hemli et al. [54] in 2020 agree in stating that robotic MIDCAB compared to sternotomy is associated with a reduction in the length of HCU stay and total in-hospital stay, a reduction in blood transfusion rate, no wound infections, less overall pain perception, faster recovery, and faster return to work. Robotic Total Endoscopic Coronary Artery Bypass (TECAB) was first time performed by Didier Loulmet and Alain Carpentier in 1998 to four male patients (mean age 59 +/− 6 years) at the Hôpital Broussais in Paris [55] and in 1999 Friedrich-Wilhelm Mohr and Volkmar Falk [56] and colleagues replicated the procedure in Leipzig. TECAB is the sublime form of minimally invasive coronary surgery because the whole operation is closed-chest performed. LIMA and RIMA are robot-harvested and coronary anastomosis is sutured through trocars by robotic instruments. MIDCAB is an off-pump single vessel procedure, meanwhile, TECAB can be performed either on a beating or arrested heart using a peripheral cannulation for cardiopulmonary bypass (CPB) and endoscopic technique for cross-clamping and cardioplegia. Gobolos et coworkers [57] in 2019 reviewed 2397 cases of TECAB and they reported 0.8% of perioperative mortality, 0.1% of stroke rate, and 1.6% of acute kidney injury which received renal replacement therapy. In 2018 Leonard et al. reported the results from a metanalysis of all TECAB which were performed between 2000 and 2017. They also found 0.8% perioperative mortality, 1.5% of stroke, 2.28% of myocardial infarction, and 95% of graft patency at 10-month follow-up. These encouraging results are achieved despite the longer operative time which was required for TECAB, the 4.2% of bleeding that required re-exploration, and the significant rate of conversion to open surgery which reaches 10% in Bonaros et al. [39] multicentre experience.

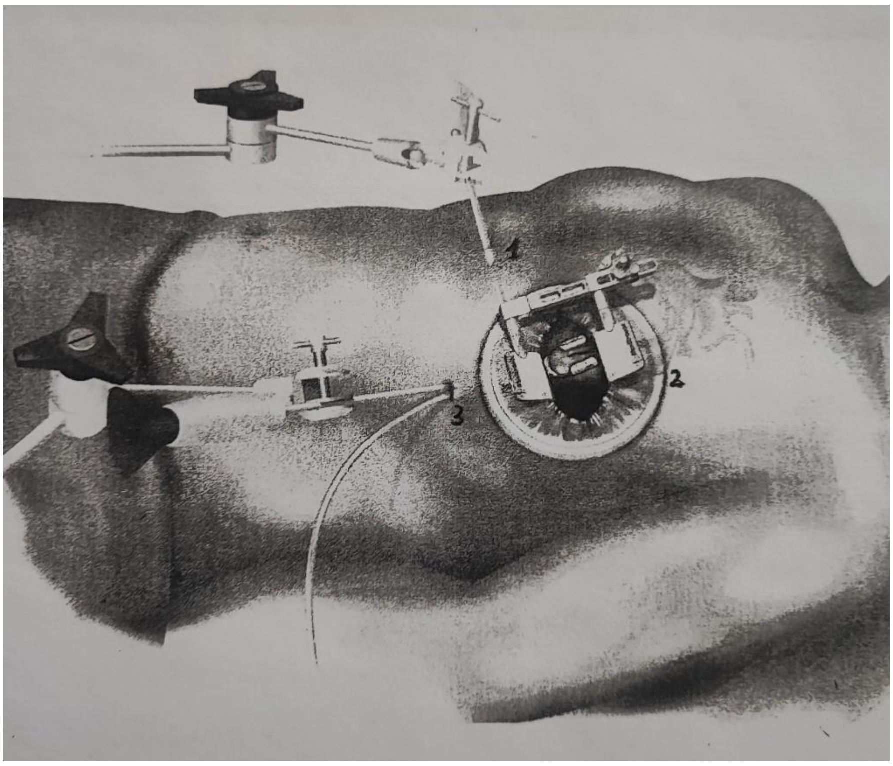

Figure 2. MIDCAB surgical setting scheme (1 stabilizer port; 2 left anterior minithoracotomy with circumferential wound protector retractor and rib retractor; 3 stabilizer port + carbon dioxide tube).

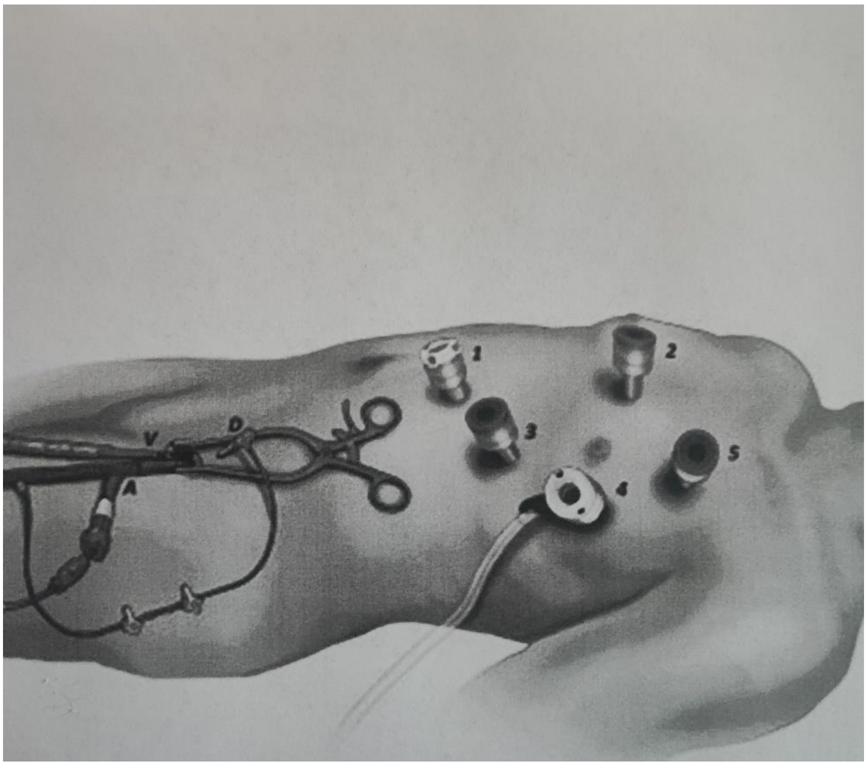

Figure 3. TECAB surgical setting scheme (1 stabilizer port 12 mm; 2 working port 12 mm; 3 left robotic arm 8 mm; 4 camera port 12 mm + carbon dioxide tube; 5 right robotic arm 8 mm).

TECAB Surgical setting—similar to the three-trocar technique of MIDCAB, which is previously described, the stroke rate of TECAB can be reduced by opting for a beating no-touch technique or arrested heart and peripheral cannulation which is to be established only after the assessment of the status of aorto-ilio-femoral atherosclerosis. **Figure 3** presents the TECAB surgical setting. A computed tomography (CT) angiogram of the chest, abdomen, and pelvis can guide the choice to beating or arrested heart [58–61]. If there are concerns about risk rate related to arterial retrograde flow, the surgeon can choose a beating heart strategy or she/he can use the right axillary artery to start an antegrade perfusion regimen in an arrested heart setting, or retrograde perfusion through the femoral artery and vein drainage through the femoral vein, while the endo-aortic balloon (EAB) is placed for the endo-clamping maneuver. In this case, transoesophageal echocardiography (TEE) is mandatory to check the right position of cannulas and EAB through which cardioplegia can be delivered if aortic valve incompetence is trivial, otherwise, retrograde cardioplegia in coronary sinus and ventricular fibrillation can be used.

4. Anaesthetic aspect

General anaesthesia is performed by balancing standard titrated and controlled intravenous induction of agents such as Propofol or Etomidate and maintenance with volatile inhalation agents, narcotics, and paralytics. Paralysis has critical importance to ensure adequate surgical visualization, reduce injury to internal structures, and minimize insufflation pressures with robot-assisted cardiac surgery. Pain management in robot-assisted coronary surgery is of paramount importance, especially given a fast-track path. Narcotics should be used sparingly at the end of the procedure to prevent delay in extubating point, early mobilization, and discharge from the hospital. Multimodal analgesia, including neuraxial and regional anaesthetic techniques, should be strongly considered. However, neuraxial anaesthesia may be contraindicated, in particular in patients undergoing hybrid procedures with drug-eluting stents (DES) necessitating the use of antiplatelet medications. New advancements in ultrasound-guided chest wall nerve and plane blocks may prove to be most beneficial without some of the additional risks associated with neuraxial techniques in robot-assisted cardiac surgery. Paravertebral blocks, by single shot or continuative infusion through catheter placement in peridural space for 48 h after surgery, have been extensively studied both in cardiac and vascular surgery and they are very effective in providing postoperative analgesia while reducing the effects of sympathetic blockade in minimally invasive robotic cardiac surgery. Intraoperative intercostal blocks also are used commonly by surgical or anaesthetic teams for robotic cardiac and thoracic cases. These blocks often are performed with either Bupivacaine or Liposomal Bupivacaine and have been shown to have efficacy for these types of cases. Serratus anterior plane blocks have been shown to provide the most significant benefit for robotic cardiac surgery. These plane blocks have been used extensively in thoracic surgery for post-thoracotomy pain. Intercostal nerve cryoablation has been described previously as an effective method for the relief of thoracotomy incision during minimally invasive direct CABG procedures and likely would prove beneficial in patients undergoing robot-assisted cardiac surgery, in particular when mini-thoracotomy is performed.

One-lung ventilation is required. One-lung ventilation can be obtained using a bronchial blocker, double-lumen ETT, or Univent tubes. Specific to robot-assisted coronary surgery, a 7.5 mm or larger ETT with a bronchial blocker is preferred to double-lumen tubes (DLTs), aiming to fast-track extubating without changing tube (from Carlens to standard tube). Defibrillation pad placement is critical. Use of internal paddles is not feasible, and emergency defibrillation may be required, especially during pericardial incision and manipulation or in the event of an emergency conversion from robot-assisted-CABG to sternotomy-CABG. Placement of defibrillation pads is opposite normal practice or on the nonsurgical side, with the round, anterior pad placed on the right anterior portion of the chest and the rectangular pad placed on the back-left side of the chest. Communication with the operating room team is a key point, specifically regarding hemodynamic goals and the amount of pharmacologic support necessary to care for the patient at different stages in the procedure. Blood pressure fluctuations and hemodynamic instability can occur at any point in the procedure. In addition, right ventricular strain can occur after one-lung ventilation is initiated and may require a change in insufflation pressures or inotropic support. Hemodynamic support is provided using standard vasoactive and inotropic agents such as epinephrine, phenylephrine, norepinephrine, or vasopressin, to achieve the desired effect. Milrinone also may be used if tolerated by the patient. In the event of ventricular arrhythmia, the surgeon should be notified immediately, because if external defibrillation is required, all instruments must be quickly removed from the chest, and reinflation of the left lung occurs before shock delivery. Reinflation of the left lung is mandatory otherwise the Capnothorax (CO_2 is usually maintained around 10–15 mmHg) significantly impedes conduction of the electrical discharge via defibrillation. If venous drainage is not sufficient, a superior vena cava cannula may be placed through the internal jugular vein. A coronary sinus (CS) catheter also may be necessary and it is placed by the anaesthesiologist via the right internal jugular vein under TEE guidance. The TEE is also useful to check EAB position during on-pump coronary surgery and after the weaning from CBP because it allows finding aortic dissection which is related to the EAB delivery or the arterial retrograde flow (in case of femoral arterial cannulation), and left ventricular wall motion abnormalities which are related to surgical procedure as Fritzgerald et al. [62] and Bhatt et al. [63] recently summarized.

5. Comment

Despite the charm of robotic coronary surgery, this program is difficult to take off due to the low confidence in working in the closed chest cavity for most heart surgeons. Oehlinger et al. [64] stated that after 100 LIMA harvesting there is a marked improvement in time to spend, meanwhile, Bonatti et al. [65] and Kappert et al. [66] stated that surgeons turn the time corner respectively after 38 or 35 robotic LIMA harvesting. Hemli et al. [67] measured at least 77 cases before the time speed up the LIMA harvesting. The learning curve is the key point, but a simulator can be used to train and speed surgeons and trainees. On the other hand, one of the main limits that affect the spreading of coronary robotic surgery is the procedural cost because the Surgical System is per se expensive and the costs are also incremented due to the fixed usage life (only 10 times) of robotics instruments and due to needs of single-use consumable devices [68,69]. However, if surgeons push to increase cases, costs can be low, the learning curve can speed, and time to procedure can also be reduced as Whellan et al. [70] in 2016 and Balkhy et al. [71] in 2020 respectively reported. Meanwhile, the exposure to new features and issues, which could arise from a different way to approach coronary surgery and combined coronary and valve surgery, can open new research fields aiming to solve rising problems and ameliorate overall surgical performances. According to literature data, it is also to be considered that robotic surgery significantly reduces ICU and in-hospital length of stay, overall postoperative, mid and long-term mortality, need for blood transfusion, and time to come back to work [36–43]. It also makes the risk of wound infection close to zero and it is perceived as less invasive and therefore more accepted by patients, also promoting psychological well-being [72]. Because robot-assisted cardiac surgery includes a large panel of heart procedures, it is reasonable to aim to combine them [10,71,72]. For example, mitral valve surgery and coronary artery surgery, in the future can be simultaneously treated in a robot-assisted single shot, instead of performing hybrid robotic-valve surgery and percutaneous coronary intervention before or after surgery. The same argument is for aortic valve surgery (AVS) and concomitant coronary artery disease (CAD) [73,74]. The recent data from the EXCEL trial pointed out that PCI with second-generation DES is no inferior to CABG on clinical and functional outcomes at 3 years following revascularization of the unprotected left main lesions. According to this trial, the repeat revascularization rates were higher with PCI than with CABG, while the thrombosis (in-stent vs. in graft) rate was lower with PCI than with CABG. Adverse clinical events were not uniformly distributed from a temporal standpoint between the two arms of the study. The hazard was highest with CABG in the first 30 days and clinical outcomes were better with PCI up to 30 days. However, this reversed between 30 days and 3 years, such that outcomes were inferior with PCI compared with CABG beyond this time frame. This was also noted out to 5 years [75]. Based on these recent findings, the need to make a choice, which is balanced on the patients' risk score profile, life perspective, and long-term procedural duration is felt even more [76,77]. If we add the changes in the recent international TAVI guidelines [78,79], which have widened the indication from high-moderate to low-risk patients, we can immediately perceive the need to find an alternative surgical strategy in case of AVS and concomitant coronary artery disease CAD for which the standard surgery with the CBP is contraindicated or not preferred by patients. With this in mind, hybrid-MIDCAB (LIMA-LAD + PCI on others) or TECAB plus TAVI to guarantee a complete surgical myocardial revascularization where it is necessary and may represent a promising minimally invasive hybrid alternative to treat AVS associated with any level of severity of CAD. Two main issues are to be addressed in the field of robot-assisted coronary surgery training and data collection to improve the robotic technique and globally measure its results. The first one is a common teaching training program, as the European Association of Cardiothoracic Surgery (EACTS), the American Association of Thoracic Surgery (AATS), the Society of Thoracic Surgery (STS), and Sutter et al. [80] recommend in 2024, and the second aspect is the way forward in research on robotic cardiac surgery that is to say the need for transatlantic robotic cardiac surgery registry to check long term follow up as Mori et al. [81]

reported in 2024. Lastly, Gianoli et al. [82] presented a detailed cost-analysis in the Netherlands. They observed that the adoption of robot-assisted-MIDCAB did not cause a significant economic impact on hospital resources because the additional robotic costs for the surgery were almost entirely offset by the cost savings for the postoperative hospital stay. However, these comparisons may differ when considering hybrid coronary revascularization with its additional percutaneous coronary intervention costs. In 2024, Dokollari et al. [83], in US, have reached the same conclusion. In fact, in a mature practice, robotic-assisted coronary surgery decreases hospital length of stay, leading to reduced hospital costs compared with conventional CABG.

6. Conclusion

Despite the evidence that benefits are related to MIDCAB and TECAB, till now they represent only 0.5%–1.0% of CABG volume in the Netherlands and similar trends are detected in the EU and US. The main issue should be related to the learning curve and costs. If surgeons push to increase cases, costs can be low, the learning curve can speed up, and time to procedure can also be reduced, with many advantages for patients' outcomes and wellness. Meanwhile, technical issues as the lack of tactile feedback in the robotic system could be addressed with further advances in technology. Moreover, higher resolution screens, smaller instruments, incorporation of augmented reality tools, intraoperative ultrasound devices, and angiographic devices can facilitate and make each robotic procedure both in the presence and a tele-remote setting. We are confident that robotic heart surgery is burgeoning and the new generation of cardiac surgeons has to face a gorgeous future if we will invest in training and technology.

Conflict of interest: The authors declare no conflict of interest.

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