Chapter

Robotic Coronary Artery Bypass Grafting: History, Current Technique, and Future Perspectives

Ekin Guran, Andrea Amabile and Gianluca Torregrossa

Abstract

Coronary Artery Bypass Grafting surgery is the most commonly performed and thoroughly examined adult cardiac surgery procedure in the world. Minimally invasive techniques which include Robotic-Assisted Minimally Invasive Direct Coronary Artery Bypass Grafting and Totally Endoscopic Coronary Artery Bypass Grafting have been helping to lessen the postoperative complications, pain, and length of stay, while enhancing postoperative quality of life of patients. However, practical application of these advanced procedures has yet to be broadly mastered for expanding the usage of minimally invasive robotic assisted techniques. This chapter describes the development and application of Minimally Invasive CABG procedures as well as the current knowledge and future perspectives on Robotic-Assisted CABG procedures.

Keywords: coronary artery bypass grafting, minimally invasive coronary artery bypass grafting, robotic-assisted minimally invasive direct coronary artery bypass grafting, totally endoscopic coronary artery bypass grafting, CABG, robotic-assisted CABG, TECAB, minimally invasive CABG, robotic CABG, robotic cardiac surgery

1. Introduction

Rapidly developing technologies in the field of surgery have encouraged the shift of conventional techniques towards minimally invasive methods.

Since cardiovascular diseases are the leading cause of death worldwide, causing the greatest threat to public health, it is perfectly reasonable to implement practice with technological advancements to treat cardiovascular diseases with minimally invasive approaches [1].

Robotic-assisted surgery offers the clinical benefits of a minimally invasive approach as well as technical advantages such as enhanced precision and visualization.

Minimally invasive procedures employed in surgical coronary revascularization include Minimally Invasive Direct Coronary Artery Bypass Grafting (MIDCAB), Robotic-Assisted MIDCAB, and Totally Endoscopic Coronary Artery Bypass Grafting (TECAB). MIDCAB is a less invasive method of Coronary Artery Bypass Grafting (CABG), in which the surgical access is obtained by a left anterior mini-thoracotomy, instead of a conventional sternotomy. In robotic-assisted MIDCAB, the left internal thoracic artery (LITA) harvest is performed with the robotic platform and is then followed by a direct anastomosis sewn through a small thoracotomy incision. Finally, TECAB is the entirely endoscopic version of the procedure, in which the robotic platform is used for both graft harvesting and coronary anastomosis.

Robotic MIDCAB and TECAB can both be done either on beating heart or on arrested heart, with the aid of cardiopulmonary bypass (CPB) support or not. Whether the operation is conducted on a beating or arrested heart is decided cautiously, considering the vascular status of the patient since the arrested heart approach may provide a better quality of anastomosis. Not only is CPB obligatory on the arrested heart approach, but it also comes in handy on a beating heart approach in patients with poor blood gas exchange, or with multiple vessel disease additionally to badly constructed vascular status [2].

In this chapter, we discuss the currently available robotic-assisted CABG strategies, including Robotic-Assisted MIDCAB, robotic TECAB with the aid of cardiopulmonary bypass (CPB), either on a beating or arrested heart, as well as robotic TECAB without the aid of CPB to achieve single or multivessel coronary grafting performed either with the robotic anastomotic device or in a hand-sewn fashion.,

2. History of robotic cardiac surgery

The use of robotic assistance in surgical procedures dates back to 1985, when Kwoh et al. used a robotic system to improve the accuracy of CT-guided brain tumor biopsies [3]. Davies et al. later used robotic techniques for transurethral resection of the prostate in 1991 [4]. Peaked interest in robotic applications in surgery led to the development of new robotic systems. In 1996, Carpentier et al. conducted the first robot-assisted cardiac procedure, which was a mitral valve repair [5]. In 1999, Mohr et al. [6] and Loulmet et al. [7] performed CABG with the aid of a robotic platform. Over time, robotic-assisted CABG procedures evolved from single-vessel to multi-vessel, and its use has since then expanded to the integration with hybrid applications.

3. Advantages

3.1 Clinical advantages

The shift of conventional procedures towards minimally invasive approaches has allowed patients to benefit from surgical treatment with fewer postoperative complications, reduced morbidity associated with surgical trauma, and shorter length of stay while enhancing the postoperative quality of life and cosmetic outcomes [8].

Robotic-assisted MIDCAB offers a minimally invasive alternative to the traumatic median sternotomy performed in conventional CABG by providing access to the thoracic cavity through a less traumatic left anterior mini-thoracotomy. This approach reduces postoperative pain scores, and also eliminates the usual risk of poor healing following median sternotomy, thus reducing the length of postoperative hospital stay [9, 10].

Sternotomy prolongs the recovery duration and bears the risk of poor healing and deep sternal wound infection (DSWI). Despite the fact that DSWI has a low incidence (between 0.2% and 3%), it is a deadly complication, and it weighs a heavy burden on healthcare with the need of repeated surgical interventions, prolonged length of stay, lower quality of life after CABG surgery, with higher costs [11–13]. Patients with comorbidities such as diabetes mellitus, chronic obstructive pulmonary disease, obesity, peripheral vascular disease have an increased risks of DSWI [14–17] Also, female sex, older age, bilateral internal thoracic artery take-down are independent risk factors on that matter [16–19]. Thanks to its minimally invasive properties, TECAB surgery reduces the risk of DSWI even in BITA take-down surgery [14, 20, 21].

The postoperative overall quality of life is improved in both robotic-assisted CABG and conventional CABG, thanks to enhanced myocardial perfusion obtained by coronary revascularization. Nevertheless, while patients undergoing TECAB achieve this rather rapidly, those undergoing conventional CABG reach the same level of comfort much later due to the greater invasive nature of the sternotomy [22].

In terms of outcomes, robotic-assisted CABG graft patency rates were found to be equivalent to outcomes of the conventional technique [23]. TECAB has yielded excellent results, even in patients with a high risk of mortality [24].

3.2 Technical advantages

Robotic-assisted minimally invasive procedures have enabled surgeons to perform surgical procedures with enhanced vision, precision, control, and dexterity [25]. Although the lack of haptic feedback was initially observed as a limitation for robotic surgeons, the Da Vinci system provides outstanding 3D visualization to observe the displacement of tissues which compensates for the lack of tactile feedback [26]. In addition to greatly improved visualization, robotic instrumentation also provides several technical advantages. Built-in motion scaling converts large natural movements to ultraprecise micromovements, and tremor filtration allows smoother and more precise motions of the articulating instrument at the surgical site [27, 28]. The wristed robotic instrumentation and robotic arms provide seven degrees of freedom (three for translation, three for rotation, and one for grasping), rather than only four degrees of movement maintained by the endoscopic devices [29]. Furthermore, robotic-assisted surgery eliminates the "fulcrum effect", otherwise faced by long-shafted endoscopic instruments, in which the hand of the surgeon and the tip of the instrument moves in opposite directions [30].

4. Disadvantages

As CABG surgery is the most commonly performed and adult cardiac surgery procedure worldwide, there has been a growing interest in robotic-assisted CABG. However, despite the initial enthusiasm, it did not become as widespread as expected, for reasons such as its steep learning curve, the requirement of an experienced surgical team, and its higher costs [31].

5. Patient selection

Each patient should be individually assessed by a multidisciplinary team of cardiac surgeons and cardiologists to determine the best approach regarding myocardial revascularization. Clinical status, associated comorbidities, and anatomical features should be considered when determining the appropriate strategy for myocardial revascularization.

Robotic-assisted CABG is more frequently used to treat total occlusion or ostial stenosis of the left anterior descending (LAD) artery, and occasionally to treat proximal LAD stenosis which is unsuitable for percutaneous intervention. Robotic-assisted CABG is also feasible in the treatment of multivessel disease, though rarely performed, in which both ITAs and a second graft can be used individually or with sequential anastomosis techniques [2].

Minimally invasive CABG may also be integrated with a hybrid approach, i.e., achieving simultaneous or delayed complete revascularization with both CABG (usually for the left coronary system) and percutaneous coronary interventions (PCI) (usually for the right coronary system), providing patients with the advantages of each technique in the least invasive manner possible [32].

Robotic-assisted MIDCAB is one of the most commonly performed robotic-assisted CABG procedures around the globe [33]. This is often conducted off-pump and consists of the endoscopic harvesting of the LITA with robotic instrumentation followed by direct anastomosis of the left anterior descending (LAD) artery through a left anterior mini-thoracotomy. Robotic MIDCAB may be preferred in patients with isolated disease of the LAD, or within the framework of hybrid coronary revascularization (HCR) strategy to treat patients with multivessel coronary stenosis along with PCI to all diseased non-LAD vessels [34]. Although robotic MIDCAB is not optimal for hemodynamically unstable patients, patients with limited pulmonary reserve or patients with significantly impaired left ventricular systolic function, favorable outcomes have been previously reported [35].

Although patient selection for robotic-assisted CABG was initially limited to non-redo patients with isolated single-vessel or double-vessel disease rather than multi-vessel disease and those with preserved ventricular function, inclusion criteria has since then broadened to include also redo patients, provided one internal thoracic artery (ITA) is still adequate for grafting. Studies have demonstrated that the procedure was viable in patients with a history of previous open CABG [36], MIDCAB [33], and TECAB [37].

In current practice, many patients with a confirmed indication for surgical myocardial revascularization can be deemed as candidates for robotic-assisted CABG. Potential contraindications include acute myocardial ischemia, serious multi-organ dysfunction, severe pulmonary dysfunction, restricted workspace inside the thoracic cavity (e.g., in severe pectus excavatum), thoracic adhesions, and obesity (BMI > 35 kg/m2) [38]. Relative contraindications to TECAB are serious left pleural fibrosis in patients with a history of chronic lung disease or lung surgery. Management with an off-pump approach may not be always feasible in patients with severely impaired lung function and peripheral cardiopulmonary bypass (CPB) support to enhance gas exchange may be considered in these cases. Emergent procedures and patients with advanced left ventricular systolic dysfunction potentially requiring advanced postoperative myocardial support are currently ruled out [32].

6. Anesthetic approach

Team coordination and communication are fundamental aspects to prevent complications in any surgical operation. This is especially important during robotic-assisted surgery, considering the physical distance between team members. Therefore, we recommend that all team members (consisting of a console surgeon, tableside assistant, anesthesiologist, perfusionist, circulating nurse, and all others who are involved) are equipped with Bluetooth headsets to ensure smooth and effective communication.

To be on par with rapid advancements in the field of robotic surgery, anesthesiologists had to overcome new challenges such as longer surgical times, problems with single-lung ventilation in the presence of coronary artery disease, and enhanced expertise in transesophageal echocardiography (TEE) [39]. Other drawbacks include the higher physical distance from the patient than usual, dealing with a bulky device onto the operative field, managing the specific patient positioning, and maintaining patient immobility while preventing prolonged postoperative recovery time due to the excessive use of neuromuscular blocking agents.

Because of the reasons stated above, robotic-assisted CABG procedures require an experienced cardiothoracic anesthesiologist. The console surgeon, tableside surgeon, and anesthesiologist must all be coordinated and in harmony throughout the entire procedure.

Anesthetic management consists of single-lung ventilation, as well as right radial artery pressure monitoring and central venous catheterization for hemodynamic monitorization throughout the surgery. Single-lung ventilation may be accomplished with either a double-lumen endotracheal tube or a single-lumen endotracheal tube with the usage of a left endobronchial balloon blocker. External defibrillator pads should be located across the heart beforehand, one on the right lateral chest and the other one on the left scapula. Near-infrared spectroscopy (NIRS) is also strongly advised to prevent postoperative cognitive dysfunction [40].

Due to the closed nature of the operation, monitoring TEE throughout the procedure is essential. TEE contributes invaluable information regarding baseline cardiac capacity and may be used to diagnose undetected pathologies. TEE ensures secure and a pinpoint positioning of guidewires and cannula for peripheral cardiopulmonary bypass. TEE is imperative for the management and safety of robotic CABG procedures since it allows for immediate detection of rare but catastrophic complications of peripheral cannulation, including superior vena cava injury or aortic dissection [41].

7. Surgical procedure

7.1 Patient positioning

Some preliminary steps including patient set up, cardiopulmonary perfusion, placement of the ports, and robotic-assisted harvesting of LITA are in the same manner for both robotic-assisted CABG surgeries. While the MIDCAB procedure continues with de-novo incision after LITA harvesting for making a direct hand-sewn anastomosis between the LITA and the coronary target, the TECAB procedure continues with robotic-assisted coronary anastomosis [31].

After the left lung is deflated, three robotic ports are placed into the left thoracic cavity under direct view. First, the camera port is located in the left fourth intercostal space in the anterior axillary line. The right and left robotic instrument ports are placed under endoscopic visualization in the second and sixth intercostal spaces, respectively, in alignment with the camera port.

The robotic-assisted anastomosis part of the TECAB surgery requires two additional ports which should be placed after robotic ITA harvesting and graft preparation. A 12-mm 4th robotic port is used to insert the Endo-wrist™ stabilizer, placed in the left subcostal space, medial side of the midclavicular line. And finally, to deliver the Cardica Flex A™ anastomotic device, a 15-mm port (Ethicon Surgical, Somerville NJ) is inserted in the 2nd intercostal space on the left midclavicular line.

After the ports placed, the table is lowered and tilted 10° to the right, and the da Vinci Si system (Intuitive Surgical, Sunnyvale, California, United States) is docked with the robotic cart, which is generally located at approximately 60° angle to the table from the right side. This positioning is to decrease the interference between the robotic arms.

Continuous warm humidified CO2 insufflation should be maintained to properly dilate the surgical area and provide sufficient pleural workspace. Intrathoracic pressure must be kept within 8–12 mmHg not to compromise hemodynamic stability. Air insufflation systems should be used at low levels since excessive use of insufflation may cause endothelial damage. We recommend maintaining the CO2 insufflation settings while entering the right thoracic cavity for BITA harvesting. Of note, using two CO2 insufflation is convenient in TECAB surgery to protect the vascular structures and heart itself from injury as a result of a sudden loss of pressure.

7.2 Cardiopulmonary perfusion and myocardial protection

Robotic-assisted CABG can be executed either on an arrested or beating heart. Whether the operation will be performed with the arrested or beating heart approach is decided cautiously considering the vascular status of the patient since the arrested heart approach may provide a better quality of anastomosis. CBP support is obligatory in the arrested heart approach. But it is not the only case that requires CBP support. It can be also used in the beating heart approach to improve poor blood gas exchange and in patients with multiple vessel disease additionally to badly constructed vascular status [2].

Considering arrested heart or beating heart surgery in need of hemodynamic or pulmonary support, the peripheral CPB method is usually the chosen one. The CPB support during TECAB is considerably low (less than 2%) and most of which used to improve gas exchange rate during single lung ventilation [31].

Since peripheral CPB support is recommended in case CPB is needed, femoral vessels should be prepared. A transverse left inguinal incision is made above the inguinal ligament to expose the femoral artery and vein. Firstly, a 4–0 polypropylene purse-string suture is implanted in each vessel which is followed by tourniquet application. Then, the introduction of a perfusion cannula with a sidearm (21-F or 23-F) into the femoral artery is underway. At last, cannulation of the femoral vein with a 25-F venous cannula is performed.

IntraClude™ balloon occlusion catheter (Edwards Lifesciences, Irvine, CA, USA) or a mechanical cross-clamp (e. g. Chitwood™, Scanlon International, Minneapolis, MN, USA) with antegrade cardioplegia are the preferred tools to be used during aortic cross-clamping and cardioplegia delivery. Because of the reason that pulmonary artery interposition makes cross-clamping the aorta from the left chest to be technically challenging, balloon occlusion catheter remains to be the preferred one.

TEE guidance is essential during the insertion of the IntraClude™ balloon occlusion catheter towards the aortic root. The balloon should be placed above the sino-tubular junction, and well below the brachiocephalic trunk. Antegrade, cold blood cardioplegia should be administered repeatedly according to the chosen cardioplegia solution.

7.3 ITA harvesting

After the endoscopic camera (30-degree up) is inserted, monopolar curved scissors are equipped to the right arm while Maryland bipolar forceps are equipped to the left one. Then dissection and reflection of the pericardial fat pad are performed. Pinpoint determination of the opening site of the pericardium is decided according to the grafting approach, since the pericardiotomy should be performed anterior to the phrenic nerve and towards the apex of the heart for LAD targets, and pericardium should be entered posterior to the phrenic nerve for circumflex marginal coronary targets. In addition, a small-scaled pericardial incision posterior to the phrenic nerve can both help drainage of the pericardial space post-operatively as well as in our belief it helps to prevent postoperative pericarditis. Since the protection of the phrenic nerve is of vital importance, care should always be taken to avoid injury during pericardial manipulation.

After reaching the surface of the epicardium, the angiogram becomes particularly useful to point out the correct coronary targets. Following the description of the targets for endoscopic grafting, attention is directed towards the ITA(s).

The two ITAs are adjacent to each other and to the heart from the endothoracic viewpoint than is commonly appreciated, considering the greater majority of surgeons only encountered them in open CABG procedures when the sternum is widely separated by a midline sternotomy incision. Thereby, either of the ITA can be used as an in-situ conduit to graft the LAD and high marginal branches.

Due to the lack of tactile feedback, excess tension should be avoided, and extra care should be taken to avoid damaging the ITAs. ITA harvesting begins from the proximal side, until its origin from the subclavian artery, to enable it to utilize its entire length. The harvesting is preferably performed as a skeletonized technique by the dissection of the artery from the fascia, intercostal muscles, and the encircling tissues to take maximum advantage of the length of the artery and also to profit from higher flow capacity [42]. This technique also assists in maneuvering the graft within the thoracic cavity and also paves the way for the assessment of the endoscopic transit-time Doppler flow. Despite the advantages of this technique, many surgeons, especially those at an earlier phase of their robotics training, still goes for the ITAs as pedicled grafts.

If the right internal thoracic artery (RITA) is to be used, it should also be the first to be harvested. Otherwise, the left thoracic artery (LITA) should be chosen without the opening of the right pleura. For both conduits, the dissection procedure is identical.

At the beginning of the RITA harvesting procedure, the finest view while dissecting of the substernal anterior mediastinal fibro-fatty tissue and during entry into the right thoracic space is given by a 0-degree robotic endoscope. After the dissection is done, the RITA should be harvested using a 30-degree (focused-up) scope. When instruments are guided into the right pleural space, it is of vital importance to prevent physical contact with the heart. Careful maneuvers should be undertaken in order to position the cameras safely near to the right pleural workspace, and the instruments should first be spotted by a direct vision from the left pleural area and then removed from there.

The endothoracic fascia and the transverse thoracic muscle are divided to uncover the vessel while harvesting RITA. For the monopolar spatula and micro bipolar forceps (20 W), a low electro-cautery setting is used to cauterize narrow vessel branches, while the larger ones should be divided with robotically applied metal clips.

The Endo-Wrist stabilizer is used to compress the anterior mediastinal tissue to optimally harvest the proximal and distal sections of the RITA. This instrument is extremely useful in TECAB surgery to help stabilize the target during the anastomosis, whether it is done on a beating or arrested heart, but it is also practical during a conduit harvesting process since it allows routine BITA harvesting regardless of the anatomical variations between the patients. It is inserted through a 12-mm subcostal 4th robotic port placed between the xiphoid process and the midclavicular line as mentioned before. When docking the fourth robotic arm a “setup joint” adjustment towards cephalic direction is recommended in order to avoid external conflicts between robotic arms.

When executing the mediastinal fat retraction with the Endo-Wrist stabilizer, care must be taken to secure that suited proximal dissection of the RITA is accomplished and adequate conduit length is provided. The 0-degree scope is ideally used to harvest the proximal RITA; the artery should be dissected up till the first intercostal branches are uncovered; then several metal clips should be used to divide the medial right internal thoracic vein. In order to widen the anteroposterior space especially in patients with narrow space between the sternum and the heart and thereby decrease the risk of instrument-induced arrhythmias, the stabilizer is then positioned on the epicardial surface while dissecting the caudal extremity of the RITA. Once the RITA is almost entirely liberated but not distally divided from the encircling tissue, attention is drawn to the LITA, which is harvested likewise as mentioned before.

The conduits are prepared with intraluminal papaverine solution injection after the harvesting of both ITAs from the loose areolar tissue is completed over their total length. A bulldog clamp is placed on the proximal RITA after heparinization. To evaluate sufficient flow through the conduit, the distal end of the RITA was occluded by a metal clip, and partially transected only the proximal site of this clip with the help of robotic Potts scissors afterward. Meanwhile, a syringe of 1:20 diluted papaverine solution connected to a 20-G Perifix® epidural catheter (B. Braun, Melsungen, Germany) is operated by the table-side assistant via the working port and then inserted tenderly by the console surgeon into the lumen of the RITA. Papaverine is injected as the catheter is removed. The table-side assistant should extract arterial blood before infusing the papaverine to confirm the correct intra-luminal catheter location. The catheter should then be slowly retrieved, and immediately after catheter removal, the RITA is distally clipped. For LITA, the same procedure is repeated.

7.4 Coronary target(s) preparation

If robotic-assisted MIDCAB surgery is the selected approach, this step continues with removing the robotic instruments and ports and expanding the camera port incision to a 5-cm left anterior mini-thoracotomy to provide direct access to the selected coronary targets, while TECAB surgery continues with robotic assistance in the rest of the procedure thereby does not need a wider thoracotomy incision. The retractors are used in Robotic-assisted MIDCAB to provide a better view similar to regular MIDCAB surgery. A pericardiotomy is performed through thoracotomy incision, which is applied anteromedially in the direction of the apical part of the heart, imitating the orientation of the LAD thus allowing the ITA to enter the pericardial space without any twist or torsion afterward. After the pericardiotomy, the LAD is exposed and can be stabilized with the help of external vacuum-assisted or pressure-assisted systems. After the coronary target preparation is finished, a direct hand-sewn graft-coronary target anastomosis is applied through the thoracotomy incision in MIDCAB surgery.

TECAB surgery, which stands out among all the surgical myocardial revascularization strategies due to its minimally invasive nature, requires two additional ports which should be placed in this stage of the procedure. A 12-mm 4th robotic port for the Endo-wrist™ stabilizer and finally, a 12 mm or 15-mm working port for coronary anastomosis instead of a de-novo thoracotomy incision.

With the help of the Endo-Wrist stabilizer, the coronary target(s) is stabilized and then exposed. Proper exposure is served by using low cautery energy with gentle opening of the overlying epicardium, which in our belief is more beneficial than sharp dissection to obtain better hemostasis in an endoscopic workspace.

The coronary target is then proximally encircled with a silastic snare Saddleloop™ (Quest Medical, Inc., Allen, TX, USA). To limit the possible venous bleeding at the coronary target sites, the silastic snare application is performed before the delivery of systemic heparinization and dividing the conduits. Upon the completion of coronary target preparation, the patient is heparinized with a specific target of activated clotting time (ACT) for each procedure acting as 300 s for MIDCAB and off-pump TECAB, while should be above 420 s for on-pump-TECAB.

7.5 Robotic-assisted coronary anastomosis, device-driven fashion

Contrary to robotic-assisted MIDCAB surgery, the coronary target anastomosis part of TECAB surgery is also completed endoscopically. There are two techniques for robotic-assisted anastomosis and applications differ depending on preference. If device-driven anastomosis is to be made, a 15 mm working port is required to insert C-Port Flex A system; on the other hand, if the hand-sewn technique is to be used, a 12 mm working port is required to embed the coronary shunts and sutures (Ethicon Surgical, Somerville, NJ, USA).

A 30-degree scope is used for better visualization. To begin with the device-driven technique, the left and right robotic arms are equipped with Black Diamond forceps. The stabilizer at the 4th port is replaced with a DeBakey forceps and the 15 mm working port is loaded with the Flex A system to perform the automated coronary anastomosis.

The Flex A device is inserted along with its neutral position which points to the diaphragm as the anvil facing heart and cartridge facing sternum and held by the DeBakey forceps. Then it is rotated in a way that now cartridge faces down while the anvil faces the sternum. Later on, the device is moved vertically to a position that faces the camera. In order to inspect and trim encircling tissue, ITA is also oriented and positioned along with the device. The placement of LITA inside the cartridge can now be ready to complete after the 10-mm linear arteriotomy. Following the placement of heels of the arteriotomy to the designated sites on the cartridge by two Black Diamond forceps, tableside assistant lowers the piercer onto the heel clip and fixates the heel of LITA onto the cartridge. During the next step, which is lowering the shield guard, slight bending of the guard can enhance the hood of the anastomosis. Then, both sides of the heel are positioned to the contrary sides of the cartridge to match with staple bays. During this placement, it is of vital importance that each staple bay is correctly matched with LITA tissue and there should be no folds in the LITA after it is properly positioned. In order to achieve this, firstly tableside assistant lowers the right-wing guard. Then, before lowering the left-wing guard, the assistant should also remove the piercer to fixate LITA in the proper place. Lowering both of the wing guards and fixation of LITA to its proper place marks the loading of the conduit so that the device can now be moved back to its neutral position and placed nearby to the target vessel on the pericardium.

The 4th port is loaded with the Endo-Wrist stabilizer once again to stabilize the coronary target. The silastic snare that encircles the coronary target which previously placed before is now tightened and hemodynamic responses and ECG alterations are observed. ST-segment elevations are tolerated since it's not necessarily a proof of ischemia but can be referred to alterations in signal detection because of the physical displacement of the heart unless followed with hemodynamic compromise. Ischemic preconditioning might be beneficial to prepare the myocardium before coronary occlusion [43].

After the coronary flow is blocked by tightening the silastic snare, a small coronary arteriotomy in the core of a previously placed CV-8 Gore-Tex suture (Gore Medical, Flagstaff, Ariz) is performed by an endo-knife (Snap-Fit; Intuitive

Surgical, Sunnyvale, Calif) using a purse-string stitch. This stitch is required to seal the insertion site of the anvil after the device is removed, since it is not part of the anastomosis. The anvil is then inserted and positioned parallelly to the coronary target. Placement of anvil inside the lumen of the vessel is crucial before moving on with the following steps of the anastomotic procedure. Then, tableside assistant activates the device and performs the anastomosis. Following the proper formation of anastomosis, the cartridge is released, the shield guard is raised, and anvil is discharged.

After the suture is tied, one should always look for potential bleeding. If that's the case, the surgeon should add additional stitches.

Occasional examination of the transit-time flow measurement (TTFM) of the graft is necessary [44–46]. In order to do this, a flexible probe through the port like Medistim (Medistim Inc., Oslo, Norway) can be used. This system provides valuable information about the procedure like mean blood flow, pulsatility index, and percentage diastolic filling. In addition, consideration of the competitive flow should also be closely examined.

If sequential grafting is needed, instead of Flex A device which is only applicable for end-to-side anastomosis, a hand-sewn technique comes into play. Thus, sequential grafting should start with the anastomotic device, then should continue with the hand-sewn approach.

7.6 Robotic-assisted, hand-sewn coronary anastomosis

Because of the aforementioned cases, in order to perform robotic-assisted coronary anastomosis, the anastomotic device is not mandatory since the hand-sewn technique is also capable of doing the same procedure.

Histological studies also prove that device-driven anastomosis can be comparable with the hand-sewn anastomosis [47–49].

It is crucial to prepare the anastomotic sites before insertion of the suture in the thoracic cavity with the endo-wrist stabilizer. In order to perform LAD anastomosis, a 30-degree down scope provides better visualization, whereas a 30-degree up (or 0-degree) scope is preferred for left circumflex branch anastomosis. Also, observing some crucial parameters like ECG alterations, variables derived from TEE, and hemodynamic responses during the 5 to 8 minutes of myocardial ischemic preconditioning is recommended. During this period, required items like shunts and sutures can be inserted into the thoracic cavity. After clamping the ITA with a small bulldog clamp, Pott scissors are used to transcend and trim to the adequate length. It is advantageous to clip the distal side of the ITA to the encircling pericardium to deal with the conduit when conducting the anastomosis. Endo-knife (Snap-Fit; Intuitive Surgical, Sunnyvale, California, U.S.) assisted arteriotomy is performed and extended with Pott scissors after a short reperfusion duration.

Both robotic arms are now equipped with Black Diamond forceps. A correct size shunt is now positioned (via the regular off-pump coronary artery bypass techniques) and the snare is released. A double-arm 7–0 Pronova suture is used to induce anastomosis in a continuous manner (Johnson & Johnson Medical, New Brunswick, New Jersey, United States). Suturing from the farthest side of the surgeon is introduced in the center of the arteriotomy, and should be completed on the adjacent side of the surgeon.

The stitches are normally carried out on the coronary artery in an outside-in fashion, but this procedure can be altered in the opposite direction only if there is the presence of calcified plaques within the coronary target wall. The graft is then parachuted onto the target artery. It is advised to insert a shunt within the conduit if there is confusion about the visualization of the heel of the conduit. The suture should be tightened in order to stop bleeding after the suture is finished. The shunt(s) should be withdrawn just before the suture is tightened.

Finally, the proximal snare and the bulldog clamp are released. After performing every anastomosis, TTFM should be evaluated with a flexible MediStim probe. If the pulsatility index is greater than 5 and the mean arterial blood flow is less than 15 mL/min, we recommend that the graft be checked.

7.7 Final surgical maneuvers

After the grafting procedures have been finalized with satisfactory results and adequate hemostasis, all the items used in the surgical procedure are cleared away from the thoracic cavity. Extra-pericardial fat that has been transferred to the lateral side is now sutured back to the medial border of the pericardium to cover the anterior face of the heart and the graft, and a 4–0 V-Loc suture (Medtronic, Minneapolis, Minnesota, United States) is used to conduct both of these procedures. The left lung is suctioned in and the lung is reinflated.

A 24-French Blake Drain (Ethicon Inc., Somerville, New Jersey, United States) is placed in the right thoracic cavity through the sub-costal port, and the second 24-French Blake Drain is also placed in the left thoracic cavity through the left port. The robot is undocked, and all the ports are removed.

If the surgery is performed on an arrested heart with CPB support, a 'hot shot' of cardioplegia or warmblood is administered before deflating the endoballoon. Only after the robot is undocked, all ports are removed, and ventilation is fully restored, will separation from the CPB support, protamine administration, and decannulation be carried out. To minimize the risk of bleeding on the port sides, it is strongly recommended to re-inspect the port sides with the scope after protamine is administered. For off-pump TECAB, this is extremely unlikely.

Finally, all port incisions are sealed with subcuticular stitches and in this way, the surgery is now completed.

8. Conclusion

At first, the TECAB technique was limited to treating single vessel disease with LITA-LAD anastomosis on an arrested heart with CPB support and in time it is proven to be safe and feasible [50, 51]. Since robotic surgical technology continues its exponential growth, the advancements in the next generations of the da Vinci robotic systems will be expected to enhance treatment options even for the high-risk patients with multivessel disease.

Robotic-assisted, totally endoscopic, off-pump CABG has been shown to be safe and feasible in treating the multivessel disease and offers outstanding results in experienced hands. To achieve successful results, the whole surgical team should master robotic surgery, and be in harmony during the procedure and in the meantime, the highest attention should be directed to the hemodynamic and hemostatic parameters of the patient.

However, the surgeons should note that robotic-assisted CABG surgery has a steep learning curve and should start with gaining experience in the treatment of single-vessel cases before progressing to multivessel procedures. Intensive training on hand-sewn suturing techniques using dry and wet-lab models is essential and highly recommended. Due to the steep learning curve and the lack of excellence centers focused on the robotic-assisted CABG, the interest from the industry has been half-hearted.

Finally, since robotic surgical technology is experiencing exponential growth and expanding its use in many specialties, it is of vital importance for us, the surgeons, to be a part of these advancements and train the next generation of surgeons accordingly in order to help them serve our society with latest minimally invasive approaches.

Author details

Ekin Guran[1]*, Andrea Amabile[2] and Gianluca Torregrossa[3]

1 University of Health Sciences, Ankara, Turkey

2 Yale University, New Haven, Connecticut, USA

3 Main Line Health, Philadelphia, Pennsylvania, USA

*Address all correspondence to: drekinguran@gmail.com

References

[1] Prevention, C.f.D.C.a. *Underlying Cause of Death, 1999-2019*. 1999-2019 [cited 2021 January 27]; Available from: https://wonder.cdc.gov/ucd-icd10.html.

[2] Onan, B., *Coronary revascularization in robotic cardiac surgery.* Cardiovasc Surg Int, 2018. **5**(1): p. 48-59.

[3] Kwoh, Y.S., et al., *A robot with improved absolute positioning accuracy for CT guided stereotactic brain surgery.* 1988. p. 153-160.

[4] Davies, B., et al., *The development of a surgeon robot for prostatectomies.* Proceedings of the Institution of Mechanical Engineers, Part H: Journal of Engineering in Medicine, 1991. **205**(1): p. 35-38.

[5] Carpentier, A., et al., *Computer assisted open heart surgery. First case operated on with success.* Comptes rendus de l'Academie des sciences. Serie III, Sciences de la vie, 1998. **321**(5): p. 437-442.

[6] Mohr, F.W., et al., *Computer-enhanced coronary artery bypass surgery.* The Journal of thoracic and cardiovascular surgery, 1999. **117**(6): p. 1212-1214.

[7] Loulmet, D., et al., *Endoscopic coronary artery bypass grafting with the aid of robotic assisted instruments.* The journal of thoracic and cardiovascular surgery, 1999. **118**(1): p. 4-10.

[8] Mack, M.J., *Minimally invasive and robotic surgery.* Jama, 2001. **285**(5): p. 568-572.

[9] Yanagawa, F., et al., *Critical Outcomes in Nonrobotic vs Robotic-Assisted Cardiac Surgery.* JAMA Surgery, 2015. **150**(8): p. 771-777.

[10] Jones, B., P. Desai, and R. Poston. *Establishing the case for minimally invasive, robotic-assisted CABG in the treatment of multivessel coronary artery disease*. in *The heart surgery forum*. 2009. NIH Public Access.

[11] Schimmer, C., et al., *Management of poststernotomy mediastinitis: experience and results of different therapy modalities.* Thoracic and Cardiovascular Surgeon, 2008. **56**(4): p. 200-204.

[12] Softah, A., et al., *Wound infection in cardiac surgery.* Annals of Saudi Medicine, 2002. **22**(1-2): p. 105-107.

[13] Graf, K., et al., *Economic aspects of deep sternal wound infections.* European Journal of Cardio-Thoracic Surgery, 2010. **37**(4): p. 893-896.

[14] Phoon, P.H.Y. and N.C. Hwang, *Deep sternal wound infection: diagnosis, treatment and prevention.* Journal of cardiothoracic and vascular anesthesia, 2019.

[15] Omran, A.S., et al., *Superficial and deep sternal wound infection after more than 9000 coronary artery bypass graft (CABG): incidence, risk factors and mortality.* BMC infectious diseases, 2007. **7**(1): p. 1-5.

[16] Grossi, E.A., et al., *Sternal wound infections and use of internal mammary artery grafts.* The Journal of thoracic and cardiovascular surgery, 1991. **102**(3): p. 342-347.

[17] Lillenfeld, D.E., et al., *Obesity and diabetes as risk factors for postoperative wound infections after cardiac surgery.* American journal of infection control, 1988. **16**(1): p. 3-6.

[18] Stahle, E., et al., *Sternal wound complications--incidence, microbiology and risk factors.* European journal of cardio-thoracic surgery, 1997. **11**(6): p. 1146-1153.

[19] Meszaros, K., et al., *Risk factors for sternal wound infection after open heart*

operations vary according to type of operation. The Annals of thoracic surgery, 2016. **101**(4): p. 1418-1425.

[20] Benedetto, U., et al., *The influence of bilateral internal mammary arteries on short-and long-term outcomes: a propensity score matching in accordance with current recommendations*. The Journal of thoracic and cardiovascular surgery, 2014. **148**(6): p. 2699-2705.

[21] Gąsior, M., et al., *Hybrid revascularization for multivessel coronary artery disease*. JACC: Cardiovascular Interventions, 2014. **7**(11): p. 1277-1283.

[22] Bonaros, N., et al., *Quality of life improvement after robotically assisted coronary artery bypass grafting*. Cardiology, 2009. **114**(1): p. 59-66.

[23] Kitahara, H., S. Nisivaco, and H.H. Balkhy, *Graft patency after robotically assisted coronary artery bypass surgery*. Innovations, 2019. **14**(2): p. 117-123.

[24] Balkhy, H.H., et al., *Robotic beating heart totally endoscopic coronary artery bypass in higher-risk patients: can it be done safely?* Innovations, 2018. **13**(2): p. 108-113.

[25] Wang, S., J. Zhou, and J. Cai, *Traditional coronary artery bypass graft versus totally endoscopic coronary artery bypass graft or robot-assisted coronary artery bypass graft—meta-analysis of 16 studies*. Eur Rev Med Pharmacol Sci, 2014. **18**(6): p. 790-797.

[26] Meccariello, G., et al., *An experimental study about haptic feedback in robotic surgery: may visual feedback substitute tactile feedback?* Journal of robotic surgery, 2016. **10**(1): p. 57-61.

[27] Prasad, S.M., et al., *Surgical robotics: impact of motion scaling on task performance*. Journal of the American College of Surgeons, 2004. **199**(6): p. 863-868.

[28] Leddy, L.S., T.S. Lendvay, and R.M. Satava, *Robotic surgery: applications and cost effectiveness*. Open Access Surgery, 2010. **3**: p. 99-107.

[29] Chitwood Jr, W.R., et al., *Robotic mitral valve repair: trapezoidal resection and prosthetic annuloplasty with the da Vinci surgical system*. The Journal of thoracic and cardiovascular surgery, 2000. **120**(6): p. 1171-1172.

[30] Dasgupta, P., A. Jones, and I.S. Gill, *Robotic urological surgery: a perspective*. BJU international, 2005. **95**(1): p. 20-23.

[31] Amabile, A., G. Torregrossa, and H.H. Balkhy, *Robotic-assisted coronary artery bypass grafting: current knowledge and future perspectives*. Minerva Cardioangiologica, 2020. **68**(5): p. 497-510.

[32] Ishikawa, N. and G. Watanabe, *Robot-assisted cardiac surgery*. Annals of Thoracic and Cardiovascular Surgery, 2015. **21**(4): p. 322-328.

[33] Balacumaraswami, L., et al., *Minimally invasive direct coronary artery bypass as a primary strategy for reoperative myocardial revascularization*. Innovations, 2010. **5**(1): p. 22-27.

[34] Hemli, J.M. and N.C. Patel, *Robotic cardiac surgery*. Surgical Clinics, 2020. **100**(2): p. 219-236.

[35] Gorki, H., et al., *Long-term survival after minimal invasive direct coronary artery bypass (MIDCAB) surgery in patients with low ejection fraction*. Innovations, 2010. **5**(6): p. 400-406.

[36] Kitahara, H., B. Wehman, and H.H. Balkhy, *Can robotic-assisted surgery overcome the risk of mortality in cardiac reoperation?* Innovations, 2018. **13**(6): p. 438-444.

[37] Nisivaco, S., et al., *Redo robotic endoscopic beating heart coronary bypass (TECAB) after previous TECAB*. The Annals of thoracic surgery, 2017. **104**(6): p. e417-e419.

[38] Bonatti, J., et al., *Robotic totally endoscopic coronary artery bypass grafting: current status and future prospects.* Expert review of medical devices, 2020. **17**(1): p. 33-40.

[39] Chauhan, S. and S. Sukesan, *Anesthesia for robotic cardiac surgery: an amalgam of technology and skill.* Annals of cardiac anaesthesia, 2010. **13**(2): p. 169.

[40] Ortega-Loubon, C., et al., *Near-infrared spectroscopy monitoring in cardiac and noncardiac surgery: pairwise and network meta-analyses.* Journal of clinical medicine, 2019. **8**(12): p. 2208.

[41] Bernstein, W.K. and A. Walker, *Anesthetic issues for robotic cardiac surgery.* Annals of cardiac anaesthesia, 2015. **18**(1): p. 58.

[42] Wendler, O., et al., *Free flow capacity of skeletonized versus pedicled internal thoracic artery grafts in coronary artery bypass grafts.* European journal of cardio-thoracic surgery, 1999. **15**(3): p. 247-250.

[43] Balkhy, H.H., et al., *Integrating coronary anastomotic connectors and robotics toward a totally endoscopic beating heart approach: review of 120 cases.* The Annals of thoracic surgery, 2011. **92**(3): p. 821-827.

[44] Neumann, F.-J., et al., *2018 ESC/EACTS Guidelines on myocardial revascularization.* European heart journal, 2019. **40**(2): p. 87-165.

[45] Kieser, T.M., et al., *Transit-time flow predicts outcomes in coronary artery bypass graft patients: a series of 1000 consecutive arterial grafts.* European journal of cardio-thoracic surgery, 2010. **38**(2): p. 155-162.

[46] Mujanović, E., E. Kabil, and J. Bergsland, *Transit time flowmetry in coronary surgery-an important tool in graft verification.* Bosnian journal of basic medical sciences, 2007. **7**(3): p. 275.

[47] Balkhy, H.H., et al., *The C-Port distal coronary anastomotic device is comparable with a hand-sewn anastomosis: human histological case study.* Innovations, 2018. **13**(2): p. 140-143.

[48] Balkhy, H.H., et al., *Multicenter assessment of grafts in coronaries: midterm evaluation of the C-Port Device (The MAGIC Study).* Innovations, 2018. **13**(4): p. 273-281.

[49] Hashimoto, M., T. Ota, and H. Balkhy, *Robotic off-pump totally endoscopic hand-sewn coronary artery bypass using in-situ bilateral internal mammary artery.* Multimedia manual of cardiothoracic surgery: MMCTS, 2020. **2020**.

[50] De Cannière, D., et al., *Feasibility, safety, and efficacy of totally endoscopic coronary artery bypass grafting: multicenter European experience.* The Journal of thoracic and cardiovascular surgery, 2007. **134**(3): p. 710-716.

[51] Argenziano, M., et al., *Results of the prospective multicenter trial of robotically assisted totally endoscopic coronary artery bypass grafting.* The Annals of thoracic surgery, 2006. **81**(5): p. 1666-1675.