Keynote Lecture Series

Historical landmarks in the development of robotic coronary bypass grafting

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Robotic technology was first used in history for the minimally invasive surgical treatment of coronary artery disease. In 1998, the first operations were carried out at the Hôpital Broussais in Paris. Thereafter, several European and United States (US) centers developed surgical concepts for robotically assisted internal mammary artery harvesting and the construction of the anastomoses, either through minithoracotomy or in a totally endoscopic fashion. Initial experiences were documented in a number of single and multicenter series published in the early and mid-2000s. Key steps in further procedure development included the introduction of a robotic endostabilizer for beating heart completely endoscopic operations, the combination with percutaneous coronary intervention in hybrid approaches, the introduction of second, third, and fourth generations of surgical robots with improvements in each iteration, the availability of anastomotic devices, and most recently, the emergence of new robotic technology companies producing interesting alternatives to the existing machines. The larger clinical series included 500 to over 1,000 patients, with clinical results that well justified the continued application of robotics. Development of robotic coronary bypass grafting has generally been slow, but at committed centers, the procedures are routine, reproducible, safe, and effective. Over 25 years of development, robotic surgical coronary revascularization has become an important component in the armamentarium of minimally invasive heart surgery.

Keywords: Coronary artery disease; bypass surgery; minimally invasive; robotically assisted; totally endoscopic

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Introduction

In the mid-1990s, heart surgeons looked somewhat enviously at their colleagues in general surgery, gynecology, urology, and orthopedics, who had developed minimally invasive and endoscopic techniques to perform their procedures with less tissue trauma. Discussions began on how less invasive coronary artery bypass grafting (CABG) could be defined, where both the reduction of thoracic incisions and limiting heart-lung machine use were discussed as potential goals. The first reports on CABG through limited incisions appeared in 1994. Benetti carried out the first left internal mammary artery (LIMA) bypass grafting procedure on the beating heart through a minithoracotomy (1). Experimental work was carried out at Stanford University to evaluate the feasibility of a totally endoscopic approach using the long-shafted thoracoscopic instrumentation available at the time (2). These attempts essentially failed in the clinical setting because classic laparoscopic instruments lacked the flexibility and dexterity required to perform the delicate surgical movements necessary for coronary anastomosis. Laparoscopic and thoracoscopic instruments can be inserted, pulled and pushed, turned and twisted, and used for grasping and cutting maneuvers. However, this was not enough for a coronary anastomosis due to the lack of several degrees of freedom. The community of less invasive coronary surgeons had to explore new technological solutions,

eventually finding them in the field of robotics. The first prototypes of robotic devices for surgery were developed in military medicine with the idea of performing procedures remotely in the field or on spacecraft (3). These devices, with integrated joints in their end-effectors, were noted to be generally well-suited for surgical maneuvers inside narrow spaces due to their seven degrees of freedom. The start-up company, Intuitive Surgical, based in Sunnyvale, California, United States of America (USA), took up the concept for commercial use and released prototypes of the later da Vinci robot for experimental and clinical trials to test the feasibility of robotically assisted endoscopic CABG. In this lecture and article, the following 25-year history of robotically assisted coronary bypass surgery is outlined.

The world's first applications of robotics in CABG—the first totally endoscopic CABG (TECAB)

In 1998, the da Vinci surgical robot was used clinically for coronary bypass surgery for the first time. These were the first surgical robotic cases ever performed in history. In retrospect, this was a huge endeavor as one of the most complex procedures in surgery was tackled. Two centers in Europe were chosen to carry out these operations: Hôpital Broussais in Paris, France, and Leipzig Heart Center in Leipzig, Germany. In Paris, Didier Loulmet and Alain Carpentier carried out four initial operations after developing the surgical concept in cadaver studies. Two clinical cases were performed as totally endoscopic coronary bypass grafting procedures using peripheral heart-lung machine cannulation and endo-cardioplegia with the Heartport™ endoballoon (Heartport, Inc, Redwood City, CA, USA). Two cases were converted to minithoracotomy. These four cases were published in the *Journal of Thoracic and Cardiovascular Surgery* (*JTCVS*) in 1999 (4).

The goal of robotic CABG soon became performing the procedure both on the beating heart and in a totally endoscopic fashion. Animal experiments were carried out at the Intuitive Surgical laboratories in Sunnyvale, California, USA, with an international team, including Volkmar Falk from the Leipzig Heart Center in Leipzig, Germany. In these tests, a dual-console robotic system was used, and the prototype of a pressure endostabilizer was developed for the stabilization of the target vessel. Following these experiments, the world's first case was carried out by Volkmar Falk, Stephan Jacobs, Friedrich Wilhelm Mohr, and their teams in Leipzig. The case was published in 2000 in the *Heart Surgery Forum* (5). Falk later created the abbreviation TECAB (totally endoscopic CABG). The team at the Dresden Heart Center, led by Romuald Cichon and Utz Kappert, followed immediately after Leipzig, reporting their case in the *JTCVS* the same year (6). In 1999, Douglas Boyd, a heart surgeon in London, Ontario, Canada, performed the first beating heart TECAB using the Zeus surgical robot developed by Computer Motion Inc., Goleta, California, USA. He also published his experience in the *JTCVS* in 2000 (7). His procedural success was a tremendous achievement, as the Zeus system had no multi-wristed instruments. For this reason, the production of this robot was later discontinued.

The first wave of robotically assisted CABG

The TECAB procedure gained some initial momentum as a multicenter trial was carried out for the United States Food and Drug Administration (FDA) clearance of the da Vinci first-generation system. FDA approval was obtained in 2004, and study results were published by Argenziano and coworkers in the *Annals of Thoracic Surgery* in 2006 (8). The trial was carried out by US and European centers and demonstrated improved clinical results compared to the results of single-vessel LIMA to left anterior descending artery (LAD) grafting through sternotomy in the Society of Thoracic Surgeons (STS) database. The study, however, included only patients operated on with cardiopulmonary bypass (CPB) and endoballoon occlusion for cardioplegia. A European multicenter case series in 2007 in the *JTCVS* reported on 117 arrested heart TECABs and 111 beating heart TECABs (9). The conversion rate for the cardioplegia version was 23% and 33% for the beating heart version, with a relatively steep learning curve. Perioperative mortality was 1.1% for the former and 2.2% for the latter. Target vessel revascularization was also higher in beating heart TECAB (4.1% versus 2.2% in arrested heart TECAB).

Decrease of TECAB and increase of robotically assisted minimally invasive direct CABG (MIDCAB)

Due to the complexity of a totally endoscopic procedure and the expensive adjunct technology needed, several active groups revisited the MIDCAB operation and increasingly performed minimally invasive CABG by harvesting one or two internal mammary arteries (IMAs) robotically and

constructing bypasses to the coronary targets through a left-sided minithoracotomy on the beating heart. Proponents of this method were Drs. Valvanur Subramanian at Lenox Hill Hospital in New York, New York, and Sudhir Srivastava of the Alliance Hospital in Odessa, Texas, USA, who published excellent clinical results in their 2005 and 2006 series (10,11) with zero mortality and overall respectable clinical outcomes. Srivastava reported a 99% use of bilateral IMA in his series. Another early proponent of the robotic MIDCAB procedure was Francis Sutter at the Lankenau Hospital in Wynnewood, Pennsylvania, USA. He used the term "precision incision" in his 2012 publication in *Innovations* (12), and managed to reduce the minithoracotomy length to below 4 cm using special anatomical measurements on the chest X-ray. One remarkable event was the fact that in 2008, a major institution, namely Emory University, changed their operative strategy from the video assisted MIDCAB procedure (Endo-ACAB = endoscopic atraumatic coronary artery bypass) to a robotically assisted version. Michael Halkos of the group published this transition in their 2012 paper on single LAD revascularization (13). In 2009, more robotically assisted IMA takedowns were carried out than videoscopic ones, and the method was thereafter used almost exclusively.

Combinations of robotically assisted CABG with percutaneous coronary intervention (PCI)

Essentially, from the very beginning of robotic technology use in CABG, surgical procedures were combined with PCI in the so-called hybrid coronary revascularization (HCR). This is true for both robotically assisted TECAB and MIDCAB. All three previously mentioned institutions—Lenox Hill, Lankenau, and Emory—promoted the concept. Nirav Patel, the successor of Valavanur Subramanian at Lenox Hill Hospital, published a propensity score-matched comparison of robotically assisted MIDCAB with sternotomy CABG in *JTCVS* in 2018 (14). He reported a lower blood transfusion rate in robotically assisted HCR (14% versus 28.5% in sternotomy CABG), and postoperative hospital stay was 5.7 versus 6.4 days. Other perioperative outcome metrics and long-term outcomes were comparable, therefore, well-justifying the less invasive, robotically assisted approach.

A remarkable step in procedure development was the world's first simultaneous robotically assisted hybrid coronary intervention by Bob Kiaii in London, Ontario, Canada. He published the case in *Chest* in 2005 (15). The availability of a hybrid operating room enabled the procedure. In a robotically assisted MIDCAB, a LIMA to LAD was placed, followed by an on-table angiogram of the graft. Having confirmed the patency of the bypass, PCI of the right coronary artery (RCA) was carried out. The first simultaneous hybrid case of robotic TECAB with PCI was performed by my team and myself at Innsbruck Medical University on an urgent basis. We also published the case in the *Annals of Thoracic Surgery* in 2005 (16). After its successful conduct, the first planned case was carried out and reported in the *Heart Surgery Forum* (17). From thereon, we conducted simultaneous hybrid coronary interventions using robotic TECAB on a regular basis at Innsbruck Medical University, the University of Maryland, the Cleveland Clinic Abu Dhabi, and most recently at the University of Pittsburg Medical Centre (UPMC) Heart and Vascular Institute in Pittsburgh.

New hope for TECAB—insights from larger TECAB series

A very important step in developing the robotic CABG procedure was the release of the second and third-generation da Vinci S and Si systems. The main advantages, compared to the first generation, were a longer reach of the instruments, which had been an occasional challenge in IMA harvesting, better optics, four arms, and Tile Pro, which enabled the view of hemodynamics and transesophageal echocardiogram (TEE) through the binocular at the console. The guided tool change feature ensured that the instruments returned back into their exact last position. Lastly, an endostabilizer as a robotic instrument was introduced. The Endowrist Stabilizer™ (Intuitive Surgical, Sunnyvale, CA, USA) was designed as a suction stabilizer that could be inserted through a 12 mm subcostal port, and was also equipped with an irrigation system to clear the anastomosis in cases of back-bleeding. This tool could also lift the heart up and expose the obtuse marginal branches and the circumflex coronary artery. Our group also employed it as an exposure device in arrested heart TECABs. This tool allowed for further development of TECAB on the beating heart. The most active early proponent of the procedure was again Sudhir Srivastava at Alliance Hospital in Odessa, Texas, USA, who later moved to the University of Chicago. He published a series of 214 completed cases in the *Annals of Thoracic Surgery* in 2010 (18). Concerning methodology, he used U-Clips™ (Medtronic, Minneapolis, MN, USA) to construct the

anastomoses. These clips were made of titanium and were placed as single interrupted stitches around the anastomosis. They were later taken off the market, probably due to insufficient demand by surgeons. However, there were advantages concerning the speed of the anastomosis, with Srivastava reporting an anastomotic time of 12.5 to 13 minutes, probably the shortest time found in the literature. Earlier publications had reported anastomotic times of 17 to 56 minutes (4-8). IMA takedown took 33 to 34 minutes, which can be regarded as very fast compared to initial publications on robotically assisted CABG, which noted IMA harvesting times in the 60 to 78 minutes range (4,5,7,8). In his paper, he noted total operative times of approximately 3 hours for single vessel TECAB, 5 hours + for double vessel TECAB, and 8.5 hours + for triple vessel TECAB. Mortality was zero for all versions of the procedure in this report. A further publication by his anesthesia colleagues at the University of Chicago in *JTCVS* two years later (19), however, noted a clear increase in postoperative morbidity with increasing grades of revascularization, and increasing operative times. Mortality in this series of 106 patients was 4.8%. The conclusion was that single vessel beating heart TECAB appears to be associated with acceptable clinical outcomes, whereas multivessel beating heart TECAB may increase morbidity and mortality.

After I had moved to the University of Maryland in 2008, I continued to cooperate with my former team at Innsbruck Medical University, and we published a series of 500 robotically assisted TECAB operations in the *Annals of Thoracic Surgery* in 2013. Nikolaos Bonaros was the first author (20). Of the five hundred patients, 78% were operated on using CPB and the endoballoon for cardioplegia, 22% received a beating heart TECAB, and 33% were multivessel TECABs. Operative time was five hours and five minutes, and IMA harvesting took 32 to 34 minutes, similar to Dr. Srivastava's experience. Our anastomoses, sutured robotically with a specially designed 7/0 polypropylene suture, took 27 minutes. Mortality was 1%, the stroke rate was 1.8%, and the mean hospital stay was 6 days. A multivariate analysis looking into independent predictors of procedure success, essentially the non-occurrence of any adverse event, showed that arrested heart TECAB LIMA to LAD, use of CPB and cardioplegia, use of an additional assistance port, and procedures that were done after 20 initial applications predicted favorable outcomes. The only predictor for procedure safety, namely the non-occurrence of death, MI, stroke, vascular complications, and long-term ventilation, was the European System for Cardiac Operative Risk Evaluation (EuroSCORE). These data may point out the utmost importance of proper patient selection and the fact that, specifically, at the beginning of a robotic CABG program, patients with few comorbidities should be selected.

In 2011, together with my team at the University of Maryland, I carried out the world's first successful quadruple TECAB procedure. The case was published in the *Annals of Thoracic Surgery* in 2012 (21). In a patient with multivessel disease, we placed a LIMA to the LAD, which also touched down on the first diagonal branch. We also constructed a right internal mammary artery (RIMA) Y-graft off the LIMA to the posterior descending artery, and a vein graft off the left axillary artery to an obtuse marginal branch. The procedure was doable but highly complex, with an extensive operative time. Nevertheless, the clinical outcome was very good.

Advanced robotically assisted hybrid coronary interventions

Due to the complexity of triple and quadruple robotic TECAB procedures, some surgeons developed advanced hybrid coronary interventions where bilateral IMA grafting was combined with PCI. I would like to especially point out the work of Dr. Jean-Luc Jansens of Erasme University Hospital in Brussels, Belgium. Dr. Jansens constructed a Y graft of LIMA and RIMA to the LAD and to the circumflex artery in a robotic totally endoscopic fashion, a procedure which was followed by PCI of the RCA on the 7th postoperative day. This method represented another world-first in robotically assisted CABG, which he published in the *Journal of Cardiac Surgery* in 2009 (22).

My teams in Innsbruck and Baltimore had also worked on this concept, and Nikolaos Bonaros published a propensity score matched comparison of robotic advanced hybrid coronary revascularization (AHR) with classic hybrid coronary revascularization (CHR) in the *European Journal of Cardio-Thoracic Surgery* in 2014 (23). There was no mortality in either group, and conversion to open surgery occurred in 4.4% of AHR cases and 0.0% of CHR cases. Operative time was longer in AHR, but length of stay was six days in both groups, and long-term survival and freedom from major events were not significantly different.

Advanced hybrid coronary intervention is, in my eyes, the most important current offering of robotic coronary surgeons. As complex coronary artery multivessel disease is, at present, the primary condition referred for surgery,

classic hybrid interventions remain relatively rare. If our community manages to perform double IMA grafting in a sternal-sparing or even totally endoscopic fashion, this approach can be elegantly combined with PCI to treat these complex cases. Patients and interventional cardiologists will highly appreciate this approach as a less traumatic option compared to open CABG.

Further advance of beating heart TECAB

The surgeon who has brought beating heart TECAB to a level of excellence is Dr. Balkhy of the University of Chicago. He took full advantage of the robotic endostabilizer and an automated anastomotic connector, the Flex A Device (Cardica, Redwood City, CA, USA), and has routinely performed single and multivessel beating TECAB procedures with this strategy. He published a series of 544 cases in the *European Journal of Cardiothoracic Surgery* in 2022 with highly remarkable results (24). Bilateral IMAs were used in 48% of patients, robotic operative time was 4 hours and 11 minutes, 46% of patients were extubated in the operating room, mortality was 0.9%, and, according to the report, only one patient suffered a stroke. Most impressive was an average hospital stay of 2.7 days. Unfortunately, the production of the Cardica Flex A device has been halted due to insufficient demand on the market, and the Endowrist stabilizer is currently unavailable for the da Vinci Xi system. Dr. Balkhy, therefore, still uses the da Vinci Si system, and he has enough endostabilizers in stock to continue his program. However, the Si will probably be phased out in the near future. Dr. Balkhy, myself, and other TECAB surgeons are working hard to find solutions for this problem.

How frequently is robotically assisted CABG been carried out?

It is a known fact that the development of this approach has been very slow, despite the fact that the first robotic procedures worldwide were CABGs. An analysis of the STS database published by Whellan and coworkers in 2016 (25) revealed that the rate of robotic assistance in CABG from 2006 to 2012 increased only from 0.59% to 0.97%, and in 2012, only 1,260 robotically assisted surgical coronary bypass grafting procedures were carried out. The corresponding number of open CABG was 97,249. Still, the results of the robotic surgeries were appealing, with a 1.2% mortality, a 0.5% stroke rate, and a postoperative length of stay of 4 days, one day shorter than in open CABG.

A recent 25-year literature review by my group, published in the *Journal of Thoracic Disease* in 2020, showed that in 74 published series of minimally invasive CABG, which included 10,925 patients, 15.8% of the patients underwent robotically assisted MIDCAB, and 15.1% underwent TECAB (26). Stepan Cerny from Na Homolce Hospital in Prague, Czech Republic, wrote up the European robotic cardiac surgery experience from 2016 to 2019 for *Frontiers in Cardiovascular Medicine* (27). The analysis revealed a steep increase in robotic cardiac surgery during the study period. 49% of the procedures were robotically assisted CABGs. What the study also showed, was that the observed mortality in robotic coronary bypass grafting, mostly MIDCABs, was less than half the mortality predicted by the EuroSCORE. This phenomenon was not seen in robotic mitral and tricuspid valve repair.

Most recent steps in procedure development

Two events from the year 2023 need to be specifically pointed out. In June 2023, Dr. Sudhir Srivastava performed a robotic coronary bypass grafting procedure using the Mantra surgical robot (SS Innovations International Inc., Haryana, India) at the Narayana Hrudayalaya Hospital in Bengaluru, India. After retiring from his positions in the US, Srivastava founded the company SSI, and started the development of a new robotic device. This robot features an open console with a screen, and works as a modular system with several robotic arms on individual columns positioned around the patient. Dr. Srivastava has publically stated on multiple occasions that his company will produce all devices necessary for robotic totally endoscopic coronary bypass grafting.

Another highly satisfactory move is the combination of robotically assisted IMA harvesting and the Total Coronary Revascularization via Left Anterior Thoracotomy (TCRAT) procedure developed by Dr. Oleksandr Babliak in Kyiv, Ukraine (28). Together with Dr. Piotr Suwalski from the National Institute of Medicine of the Ministry of Interior and Administration in Warsaw, Poland, he demonstrated such a case at the 2023 European Association for Cardio-Thoracic Surgery (EACTS) Techno College in Vienna, Austria, and the demonstration was extremely well received. The TCRAT procedure is carried out through a left-sided minithoracotomy using peripheral heart-lung machine cannulation, direct cardioplegia through the ascending aorta, and a transthoracic clamp for the induction of cardiac

arrest. Using special exposure techniques with slings around the pulmonary veins and the inferior vena cava, all branches of the coronary tree can be reached for minimally invasive multivessel revascularization. The addition of robotic IMA harvesting, compared to direct vision harvesting, ensures the full length of both internal mammary arteries and an ergonomically much more attractive takedown process. Given the challenges with beating heart multivessel TECAB outlined earlier, this might be a nice intermediate step for colleagues to tackle multivessel surgical revascularization in a robotic fashion.

Conclusion

After this 25-year journey through the development of robotically assisted coronary bypass surgery, I would like to conclude that coronary bypass grafting served as the springboard for a surgical technology company to eventually reach a broad multispecialty application of robotics in surgery. Robotic CABG has, in a stepwise manner, developed into single, double, triple, and even quadruple CABG in a completely endoscopic fashion. Both beating heart and cardioplegia versions of procedures, either through an adjunct minithoracotomy or in a totally endoscopic fashion through ports only, are feasible. Robotic CABG can be elegantly combined with PCI in classic and advanced hybrid coronary interventions. The overall development has been slow, but clinical results after individual, team, and community learning curves are very appealing. Interesting and well-functioning adjunct devices have been developed to facilitate robotic coronary bypass grafting, but due to business decisions by technology companies, several of these devices have been taken off the market. This makes further growth of the procedure difficult, specifically for the TECAB operation. New surgical robots are currently in early clinical testing, and one device has already been used for robotic CABG. There is a renewed interest in the procedure, and as the next generation of heart surgeons grows up with robotics as a routine component of the operation room, the basic skill set will already be ingrained, making it possible to develop them into competent robotic heart surgeons. All these facts lead me to be convinced that the future of robotic coronary bypass surgery is bright.

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