Surgical Technique

Fifty years of coronary artery bypass grafting

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Abstract: Coronary artery bypass grafting (CABG) remains the most common cardiac surgery performed today worldwide. The history of this procedure can be traced back for more than 100 years, and its development has been touched by several pioneers in the field of cardiac surgery, who have contributed with both their successes and failures. With ever increasing follow up and number of patients treated, thinking regarding optimal CABG technique evolves continually. This article reviews the history of CABG from its early experimental work to recent technological advances.

Keywords: Coronary artery bypass grafting (CABG); history; coronary revascularization

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Introduction

Coronary artery bypass grafting (CABG) is still the most commonly performed cardiac surgery procedure worldwide, representing annual volumes of approximately 200,000 isolated cases (1) in the US and an average incidence rate of 62 per 100,000 inhabitants in western European countries (2,3).

The journey of CABG has been embraced by many of the pioneers in cardiovascular surgery with both their successes and failures. All those contributions can be conceptually categorized into three distinct eras starting at the beginning of the last century. First, the experimental work performed up to the early 1960's with reports of some laconic but also some impressive early clinical results. Second, the modern coronary artery surgery has developed on the foundation of testing several grafts and an attempt to standardize them, which has brought along the beginning of evidence-based cardiac surgery. Third, like in other surgeries in the 21st century, the minimal invasive surgery evolves towards enhanced collaboration between conventional surgery and interventional medicine.

First era: before 1960's—experimental works and first clinical results

The development of coronary surgery can be traced back more than 100 years, when Alexis Carrel first described the concept of operating on the coronary circulation in 1910 and successfully performed intrathoracic aortic and cardiac anastomoses in dogs (4). In 1935, Claude Beck relieved his patients' angina pectoris by placing muscle pedicles, omentum, and pericardial fat inside the pericardium in order to increase myocardial blood supply (5). Arthur Vineberg further improved this concept in 1946 when he implanted the left internal thoracic artery (LITA) directly into the front wall of the left ventricle (6). The so-called "Vineberg Procedure" often led to symptomatic improvement of angina (7). The underlying method of this improvement was the development of collateral circulation to the left anterior descending (LAD) artery, which has recently been demonstrated with angiography to support cardiac function 30-years postoperatively (8). However, with the advent of direct coronary anastomosis of the LITA to the LAD, the "Vineberg Procedure" has been abandoned.

But before a step toward direct surgical repair of coronary arteries occurred, Charles Bailey performed in 1956 successful human coronary endarterectomies in seven patients (9). However, until this point in time, the main obstacle to the evolution of coronary surgery was the inability to picture the coronary arteries. The solution to this problem appeared inadvertently on October 30, 1958, when Mason Sones inadvertently injected dye contrast into the right coronary artery (RCA) of a young man with rheumatic heart disease at the Cleveland Clinic (10). He subsequently followed this inadvertent technique with the first intentional selective coronary angiogram, which led to the birth of coronary angiography, a truly landmark achievement in the history of cardiovascular care.

Before grafts were routinely used for coronary surgeries, direct operation on the coronaries advanced again in 1961, when the Swedish surgeon Ake Senning enlarged the lumen of a left main coronary artery using a pericardial patch (11). Only a few months later, on the other side of the Atlantic ocean, the Cleveland Clinic and Donald Effler applied this pericardial patch technique to both (left and right) coronaries (12).

Second era: from the 60s to the late 90s—different grafts and evidence-based medicine

The first successful CABG surgery was performed by Robert Goetz at the Albert Einstein College of Medicine-Bronx Municipal Hospital Center in New York using Rosenak (tantalum) rings (13). Previously by developing the concept and training their surgical skills, his team had performed multiple successful bypasses using this device in dogs until their landmark anastomosis was completed in as fast as 17 seconds. On May 2, 1960, Goetz led then a team of four surgeons in anastomosing the right internal thoracic artery (RITA) to the RCA of a male New York taxi driver using this device. A first angiogram on postoperative day 14 showed a patent graft. Eventually the patient died 13 months later but the autopsy revealed a still patent graft (13). Because of resentment of his medical colleagues and despite positive initial results, no additional coronary surgery was performed by Goetz and his team.

The first clinical case of a direct hand-sewn coronary anastomosis was performed by David Sabiston on April 4, 1962, when he anastomosed the saphenous vein graft (SVG) to the RCA at Johns Hopkins (14). Technically this procedure was performed off-pump using an end-to-end distal anastomosis. However, when the patient died 3 days later of a stroke, Sabiston was so dishearten by this experience and did not attempt vein bypass for almost a decade and did not report this important event until 1974. Similarly Edward Garret and Michael DeBakey in Houston also grafted a saphenous vein on the LAD on November 23, 1964, but did not report it until 1973, when they could prove a patent graft 7 years later (15). So the history more frequently attributes the first successful hand-sewn anastomosis to the Russian surgeon Vasilii I. Kolessov, who completed a suture of the RITA to the RCA without cardiopulmonary bypass on February 25, 1964. He reported the outcomes of his first 12 bypass surgeries in 1967, exactly 50 years ago (16). In 1968, Dr. George Green from the Saint Luke's Hospital in New York City performed the first LITA to LAD anastomosis (17), which has become the absolute gold standard of the CABG surgery. The CABG surgery as it is known today was born!

Experimentation with coronary surgery led first to the use of the SVG conduits. The person, who is considered to have truly established the benefits of saphenous vein CABG was Rene Favaloro, an Argentinian surgeon at the Cleveland Clinic. He performed his first bypass surgery in May 1967 on a 51-year-old male with an occluded RCA, which was repaired by an interposition SVG completed with two end-to-end anastomoses (18). A year later, in 1968, Favaloro reported the use of the SVGs in direct coronary surgery in 150 patients, with generally excellent outcomes confirmed by angiogram, setting an important landmark in the birth of modern coronary surgery. By 1970, he had performed more than 1,000 cases. Even in the early days of SVG, it was recognized that this conduit was prone to failure. Pathological reports already emerged in the early 1970s, which described intimal and medial thickening and graft thrombosis (19). Subsequent studies have proven that intimal hyperplasia and premature atherosclerosis result in lower patency of venous versus arterial conduits (20).

Definitive clinical evidence supporting internal thoracic artery (ITA) use appeared in the mid-1980s when Floyd Loop and the Cleveland Clinic reported 10-year outcomes of ITA conduits versus total vein grafting (21). They showed that the use of the ITA was associated with improved survival, reduced risks of myocardial infarction, hospitalization and for repeated revascularizations. Studies since that time have elucidated the physiologic basis for the superiority to SVGs, including resistance to the development of atherosclerosis (22) and nitrous oxide production benefiting the entire coronary system (23).

In Europe, Alain Carpentier, recognizing early that

the superiority of mammary arteries over SVGs may be extended more broadly to all arteries, first used the radial artery (RA) for aorto-coronary bypasses in 1971 (24). However, the early experience was not positive, as within a few years of adopting the RA as a graft, there were reports of early failure rates and significant intimal hyperplasia (25). As a result, RA use became virtually non-existent. This early graft failure rate was likely due to endothelial injury secondary to mechanical dilatation as well as techniques of early RA harvest, particularly skeletonization, resulting in vessel trauma and spasm. This hypothesis is supported by the revival of the RA as a conduit, which coincided with the use of vasodilators to prevent graft spasm as reported by Christophe Acar in 1992 (26), who worked closely with Carpentier. He described a "no-touch" method of graft conduit harvesting as well as pharmacological rather than mechanical vasodilatation as prophylaxis against RA spasm. An improved understanding of graft physiology and endothelial protection facilitated postoperative patency rates close to 100% later reported by the same group (27).

Another arterial graft used is the right gastroepiploic artery (GEA), whose origin is posterior to the gastric pylorus as a branch of the gastroduodenal artery and runs parallel to the greater curvature of the stomach. On February 20, 1987 a surgeon in Louisville, Abdullah Attum, reported a double CABG using the right GEA passed through an opening in the membranous part of the diaphragm into the pericardial sac and anastomosed sequentially to the posterior descending branch of the RCA and the posterior lateral marginal branch of the circumflex artery (28). This technique offers advantages such as for the patient with atherosclerotic ascending aorta because the *in situ* GEA allows an aortic no-touch technique and for redo-cases because the abdomen is a virgin area (29). According to the only few reports available in the literature we can conclude to a very low adoption among the cardiac surgeons worldwide partly due to the need to open a second cavity (abdomen), thus increasing contamination risks.

Some biologic vascular grafts have been applied in and commercialized for coronary artery surgery such as human umbilical vein graft (Biograft, Meadox Medicals, Oakland, NJ, USA), treated bovine internal mammary artery (IMA) graft (Biocor BIMA Biograft, Biocor laboratory, Belo Horizonte, Brazil), or dialdehyde starch-treated bovine artery grafts (Bioflow, Bio-Vascular Inc., St. Paul, MN, USA). However, most of those have failed because of thrombogenicity and degenerative changes. Neither synthetic grafts [expanded polyetetra-fluoroethylene (PTFE), Dacron], nor recently developed tissue-engineered grafts and polyurethanes have demonstrated satisfactory patency rates (30).

The concept of arterial revascularization is a result of the benefit observed with single ITA grafting compared to pure venous configurations. Logically, many groups postulated that two ITAs would further improve patient outcomes. A report by the Cleveland group in the late 1990's supported this hypothesis, as bilateral ITA (BITA) grafting was associated with greater survival and reduced need for reoperation when compared to single ITA grafting (31). Divergence of the survival curves initially reported at 10 years of follow-up was shown to continue in subsequent studies, which followed patients for 20 years (32,33). This association of BITA superiority persisted regardless of whether the ITA was taken down as a pedicle or skeletonized graft, whether patients were diabetic or not, and among patients of both sexes. Furthermore, following BITA, the left and right internal thoracic arteries seem to have similar long-term patency and survival benefit regardless of configuration (e.g., Y-graft versus *in situ*) (34-37), though ITAs grafted to less-stenosed and RCAs may have decreased patency (37). Despite continued scientific evidence in retrospective literature supporting BITA superiority to single ITA, the utilization of BITA remains low (38). This is due to a number of factors, including increased time and cost for BITA grafting, as well an increased risk of deep sternal wound infection (39). Ten years results of the Arterial Revascularization Trial (ART), a randomized trial of 3,104 patients who received bilateral or single ITA are forthcoming and should provide more clarity on a potential benefit of BITA (39).

Several randomized trials have compared the RA, the SVG and the free right internal thoracic artery (FRITA) as the graft of choice to the best non-LAD target. The Radial Artery Patency (40) and the Radial Artery Versus Saphenous Vein Patency (41) studies reported superior 5-year angiographically-confirmed patency with the RA on late follow-up. In contrast, a study by the Veteran Affairs cooperative study (42) and the Radial Artery Patency and Clinical Outcomes (RAPCO) study (43) reported the three conduit options to have similar patency rates. In summary, reports of excellent outcomes with the RA in addition to numerous advantages (i.e., ease of harvest, long enough to reach all coronary territories, size match with the native coronaries, uniform caliber, sternal perfusion allowed by an untouched right ITA) have led to the widespread adoption of the RA as frequently utilized arterial graft for second or

third bypasses.

Evidence supporting utilization of both the internal thoracic and radial arteries has evolved into a relatively recent push for total arterial revascularization (TAR) (44). Retrospective evidence has shown TAR to be achievable in one-third of isolated CABG patients, with long-term survival superior among TAR patients versus non-TAR patients at 10 years (45-47). When Y-/T-graft technique is used, this approach provides the additional benefit of performing a completely anaortic technique in situations when manipulation of the aorta should be avoided (e.g., porcelain aorta). The most recent American CABG guidelines state: "*Complete arterial revascularization may be reasonable in patients ≤60 years of age with few or no comorbidities (Class IIb, Level of Evidence C)*" (48). The European guidelines give a strong recommendation, stating: "*Total arterial revascularization should be considered in patients with reasonable life expectancy (Class IIa, LOE B)*" (49).

Third era: development to nowadays—minimal invasive & hybrid revascularization

Naturally minimally invasive coronary surgery has developed on the foundation of the thoracotomy in order to avoid a (full) sternotomy. First the minimally invasive direct coronary artery bypass grafting (MIDCAB) emerged in the mid-90s through an anterior mini-thoracotomy. A first set of 155 patients with isolated lesions of the LAD in Italy was reported by Antonio Calafiore (50), and the technique was standardized and later meticulously described by Valavanur Subramanian (51). Naturally this technique has turned briefly towards conventional thoracoscopy and then logically towards robotics. Historical operating systems such as the Automated Endoscopic System for Optical Positioning (AESOP) and the Zeus Robotic Surgical System have evolved to the current and only clinically available da Vinci Surgical System (Intuitive Surgical Inc., Sunnyvale, CA, USA). Although many groups refined the technique simultaneously, the first totally endoscopic coronary artery bypass grafting (TECAB) was attributed to Didier Loulmet and his team (52) in France in the early summer of 1998. Since then several teams have published their results from early series to 500 cases (53-56). Unfortunately because of the heterogeneity and the confusion that emanates from the terminology, a comparison between them is difficult. The term robotic MIDCAB is a mixed form of both techniques related above and commonly defined as the endoscopic ITA harvesting, while the anastomosis is performed by direct vision through a mini-thoracotomy. In TECAB the anastomosis is also performed with a closed chest with a running suture. Meanwhile not only single but multiple bypasses with BITA's and vein graft use, both off- (57) an on-pump (58), have been described in the literature.

A potential new area has emerged with the successful development of a distal anastomotic device in the form of a stapler (C-Port®, Dextera Surgical Inc., Redwood City, CA, USA) making the Achilles' heel of the procedure easier for cardiac surgeons without compromising the graft patency (59). Nowadays in this current era of enhanced medical technology with devices instead of manual work, more standardized ways of anastomosing grafts onto coronary arteries are needed in an attempt to improve surgical results. Also conduit harvesting has developed similarly into an endoscopic fashion. Several devices are available on the market for standardized procedures for saphenous vein and RA graft harvesting. With appropriate training the grafts quality is similar to open graft harvesting (60,61).

In parallel the cardiologists have moved towards more aggressive interventional catheter based therapy. Already in 1977 in Zürich, Andreas Gruntzig first performed the first percutaneous coronary intervention (PCI) as a transluminal balloon angioplasty to dilate a stenosis in the LAD (62). It took less than 10 years before metallic stents could be successfully folded and inserted into the coronary arteries in order to prevent arterial recoil and restenosis with the first clinical data reported by Ulrich Sigwart in Switzerland (63). The introduction of bare-metal stents brought into light the two major limiting phenomena: in-stent restenosis (with intimal proliferation) and stent thrombosis. Logically scaffolds capable of delivering drugs emerged quickly thereafter in order to counteract those problems. The first generation of drug-eluting stents (DES) made out of stainless steel and delivering sirolimus (rapamycin) or paclitaxel soon yielded to the second generation of stent materials (e.g., cobalt chromium) with decreased strut thickness reducing mechanical risk factors of incomplete stent apposition but delivering similar drugs (paclitaxel or sirolimus-derived zotarolimus and everolimus). Nowadays research aims at eliminating the adverse long-term concerns related to the polymer-induced delayed vessel healing by developing bioresorbable stents (64).

CABG remains the "gold standard" treatment for multi-vessel coronary artery disease, particularly for three-vessel or left main coronary artery disease. Several trials comparing CABG and PCI (ASCERT, FREEDOM, and SYNTAX) have reported superior long-term survival with

CABG compared to PCI in terms of survival rates (65-67). This superiority is likely attributable to the LITA to the LAD anastomosis, given that more than three-fourths and potentially all of the left ventricular blood supply comes from the left main coronary artery (68). Evidences from these trials involving thousands of patients followed for at least 3 years supports the statement that CABG should remain the standard of care for patients with complex coronary artery disease, although PCI is an acceptable alternative for patients with less complex disease. Consequently, patients with left main disease and SYNTAX score >22 are a class I indication for CABG whereas a SYNTAX score >32 is a contraindication for PCI according to the 2014 European guidelines (49).

Despite this evidence, PCI is a much less invasive revascularization procedure with less patient discomfort, shorter recovery, and lower risk of stroke (69). Furthermore, it is associated with similar long-term patency rates compared to CABG done with vein grafts (70,71). Already, newer generations of stents reported fewer restenoses and fewer repeated revascularization procedures. The RAVEL study showed almost 90% freedom from target lesion revascularization rate at 5 years (72).

Taken together, the advantages of CABG may be most pronounced for LAD lesions, while non-LAD arteries may have similar outcomes with bypass grafts or DES. This rationale has led to the development of hybrid coronary revascularization (HCR), in which the LIMA-LAD bypass graft is completed through a minimally invasive MIDCAB or TECAB, while angioplasty is performed on non-LAD arteries. This concept has been shown to be safe for more than a decade ago (73). Although hybrid techniques have already shown similar long-term outcomes to pure percutaneous revascularization in one study (74), larger randomized studies are needed to confirm these results. Those technical evolutions could slowly erase the borders between cardiac surgeons and interventional cardiologists in order to work more closely in hybrid procedures.

Conclusions

CABG surgery has a storied history ripe with successes and failures of pioneers in the field of cardiac surgery. Its development has progressed from experimental stages, to the discovery of optimal conduit selection, which was driven by patient-focused evidence, to a current era in which the method of performing the surgery has become the focus. The next era may/should concentrate more on the optimal use of the surgical and interventional resources to provide the least invasive but best long-term treatment. Those borders between cardiac surgeons and interventional cardiologists may be fading in the future.

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Footnote

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