Coronary Artery Bypass Surgery: Historical Overview and Future Directions

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Abstract
Myocardial revascularization developed as a method of treating ischemic heart disease during the mid-1940's. Throughout the years that followed, a variety of direct and indirect means of revascularization were introduced which later evolved to direct coronary artery bypass grafting. The advent of cardiopulmonary bypass years later, with cardioplegia providing further myocardial protection, revolutionized bypass surgery and permitted surgical intervention in a usually dry and motionless environment. This method, which provided myocardial protection while maintaining vital organ perfusion, became the gold standard in coronary revascularization. In recent years, however, a new era has emerged with a return to beating heart surgery and a trend towards minimally invasive procedures.

Introduction
In 1880, Theodur Billroth wrote, “a surgeon who would attempt the suture of a heart should lose the respect of his colleagues because the operation is not compatible with a surgeon’s responsibility.” Since that time cardiac surgery has progressed in leaps and bounds. It is widely agreed that the single most important development in this field is the introduction and refinement of extracorporeal circulation via cardiopulmonary bypass (CPB). The implementation of CPB, with added cardioplegia, defied the prediction of Sir Stephen Paget who, in 1896, said “surgery of the heart has probably reached the limits set by Nature to all surgery; no new method, and no new discovery can overcome the natural difficulties that attend a wound of the heart.” In fact, the benefits of CPB made a dramatic difference in the ability to provide definitive treatment for many cardiac maladies. CPB allows the surgeon to perform intracardiac (and extracardiac) procedures in a virtually quiet, motionless, and usually dry surgical environment, provided the myocardium is protected and the brain and vital organs are perfused. In 1989, Cooley reflected back on the milestones achieved in the previous three decades and divided these into four distinct periods of progress in cardiac surgery. Period I (1956-1962) saw the development of CPB with a blood primed extracorporeal circuit. Most of the patients treated suffered from congenital heart defects. The second period (1963-1969) saw an improvement in CPB techniques and more patients suffering from acquired heart disease. Period 3 (1970-1979) represented the boom in cardiac surgery, with the introduction of techniques for myocardial revascularization to treat atherosclerotic coronary artery disease. In addition, cardiac transplantation as well as valve repair and replacement were introduced. The fourth period (1980 to the time of Cooley’s writing) was characterized by the advent of interventional cardiology in which the cardiologist treated some of the diseases that would have previously required surgical intervention. Techniques included percutaneous transluminal coronary angioplasty and balloon valvuloplasty, and more recently, device-closure of atrial septal defects.

Since Cooley’s historical review, a new era has been ushered in with further insight into coronary revascularization and the resurgence of coronary bypass surgery in the absence of CPB (also known as “off-pump” surgery). This last step began the trend towards what is now called Minimally Invasive Cardiac Surgery (MICS).

Coronary Artery Bypass Surgery (CABG)
CABG is a unique microsurgical intervention requiring a large, highly trained surgical team, extracorporeal circulation, and intensive care unit resources. Although bypass surgery is quite complex, expensive, and subject to intense scrutiny, it has become the most common form of major surgical intervention. It has achieved this status because it is a successful therapy for coronary atherosclerosis, a prevalent disease in Western society.

Modern coronary bypass surgery is the result of a series of intellectual and technologic advances that extend back to the early part of the 20th century (Table 1). As early as 1910, Alexis Carrel experimented with coronary bypass grafts. Various methods were subsequently implemented to indirectly increase myocardial oxygen supply and treat angina pectoris. The first documented operation to increase myocardial perfusion in humans was Vineberg’s concept of implanting internal thoracic arteries directly into the myocardium in the hope that collateral blood flow with the coro-
nary arteries would develop. Communications did develop on occasion and some patients did experience relief of angina. However, this method of indirect revascularization was inconsistent and relief was not immediate. The first successful approach towards direct myocardial revascularization was performed clinically by Bailey in 1957 using coronary endarterectomy. Another direct intervention, patch repair of coronary stenoses, was successfully implemented by both Effler and Senning in 1962.

The second significant development in coronary bypass surgery was the introduction of coronary arteriography by Sones and Shirey. This technique was very important in the diagnosis and treatment of ischemic heart disease. By determining the location and severity of coronary artery lesions and left ventricular function, potential complications due to coronary atherosclerosis could be predicted, thus leading the way to treatment.

In 1962, based on experiences of vascular surgeons who used saphenous vein grafts for the treatment of lower extremity arterial stenoses, Sabiston extended these concepts to coronary arteries when he performed a saphenous vein graft from the aorta to the right coronary artery. Two years later in the Soviet Union, Kolessov performed an anastomosis of the internal thoracic artery to the left anterior descending (LAD) branch of the left coronary artery for the treatment of angina. However, this was attempted in the absence of coronary angiography. Contributions by Favaloro, Effler, Sones, and the Cleveland Clinic team, along with Johnson and colleagues in Milwaukee, advanced bypass surgery to being a planned procedure in treating angiographically-determined coronary stenoses. While they extended saphenous vein grafting to the left coronary system, Green added the left internal thoracic artery (LITA) as a routine coronary bypass graft.

Soon after, angiographic follow-up studies documented that many coronary bypass grafts remained patent and the effectiveness of CABG in relieving angina became evident. By the early 1970s, the techniques that form the basis of coronary bypass surgery today (ITA grafting, saphenous vein grafting, and coronary endarterectomy) were well established. Though surgical technique has changed very little over time, substantial changes in technique protecting the patient and the myocardium during and after the operation have developed. Furthermore, long-term assessment of coronary bypass patients has led to the identification of patients who will benefit the most from this procedure. By 1975, three large, multicenter, prospective, randomized trials had been initiated to scrutinize in detail the validity of coronary bypass grafting in treating angina and other cardiac complications. The Veterans Administration Cooperative Study Group for Surgery for Coronary Arterial Obstructive Disease (VA study) and the European Coronary Surgery Study (ECSS) all evaluated the strategy of immediate surgery versus initial medical management followed by surgery if symptoms worsened. Despite the variability in study design and results, these investigations provided an enormous amount of information and established that some subgroups of patients have improved survival with surgery.

As one can observe from the numerous studies and developments described above, perhaps no other operation has undergone the thorough evaluation and scrutiny encountered by coronary bypass surgery.

### Table 1

**Early History of Coronary Bypass Surgery**

<table>
<thead>
<tr>
<th>Year</th>
<th>Author(s)</th>
<th>Procedure</th>
</tr>
</thead>
<tbody>
<tr>
<td>1948</td>
<td>Kunlin</td>
<td>Saphenous vein bypass grafting of lower extremity atherosclerosis</td>
</tr>
<tr>
<td>1950</td>
<td>Murray and Murray</td>
<td>Intercostal vein grafts to coronary arteries</td>
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<tr>
<td>1953</td>
<td>Gibbon</td>
<td>Cardiopulmonary bypass</td>
</tr>
<tr>
<td>1957</td>
<td>Bailey</td>
<td>Coronary endarterectomy</td>
</tr>
<tr>
<td>1962</td>
<td>Effler and Senning</td>
<td>Patch repair of coronary artery stenosis</td>
</tr>
<tr>
<td>1962</td>
<td>Sabiston</td>
<td>Saphenous vein graft to right coronary artery</td>
</tr>
<tr>
<td>1964</td>
<td>Garrett et al.</td>
<td>Successful saphenous vein graft to left anterior descending coronary artery</td>
</tr>
<tr>
<td>1964</td>
<td>Kolessov</td>
<td>Mammary artery graft to left anterior descending coronary artery (without coronary arteriography)</td>
</tr>
<tr>
<td>1967</td>
<td>Favaloro</td>
<td>Saphenous vein graft to right coronary artery</td>
</tr>
<tr>
<td>1968</td>
<td>Favaloro et al.</td>
<td>Saphenous vein grafts to left coronary artery</td>
</tr>
<tr>
<td>1968</td>
<td>Green et al.</td>
<td>Mammary artery graft to left coronary system</td>
</tr>
</tbody>
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Adapted from Lytle, 1992

In order to develop bypass surgery as a widely used surgical intervention for coronary artery disease, two steps were essential to provide safe and reproducible results for both intracardiac and extracardiac procedures. The first was the development of cardiopulmonary bypass used clinically by Gibbon in 1953 to repair an atrial septal defect on an 18-year-old woman. Although it took nearly two decades to refine the technique, the improvements in extracorporeal circulation brought significant contributions to cardiac surgery. Although prior to this time it had been possible to perform limited operations for bypass grafting without CPB, the precise reconstructions needed to treat extensive coronary artery disease would not have been possible without cardiopulmonary support.
than the internal mammary artery when acting as a conduit between the aorta and coronary artery. Further, the greater saphenous vein is less dependent on hemodynamic factors in the patient and is less responsive to vasoconstriction related to inotropic agents. However, over time, it became increasingly evident that the saphenous vein graft had several disadvantages, the most significant of which is its long-term patency. The ten year patency for saphenous vein grafts is only 50%, whereas ITA grafts showed 85-90% patency rates over the same ten year period. In a fifteen year follow-up of patients post-operatively, Cameron and colleagues also found significantly better survival and freedom from cardiac events for patients who had received one or more ITA grafts. They compared those with who had saphenous vein grafts only. It should be noted, however, that many of these studies were conducted in the absence of modern day cholesterol lowering agents, which are known to slow the atherosclerotic process.

Since the studies involving the ITA, there has been increased interest in other arterial conduits. These include the gastroepiploic artery (GEA), the inferior epigastric artery (IEA), and the radial artery (RA), which have all been considered as supplements to the ITA. Although a theoretical advantage for the use of arterial conduits exists, their superiority has yet to be borne out in long-term studies. In addition, these arteries are more difficult to harvest, more easily damaged, more demanding to anastomose owing to their fragility and small size, and more compromised by spasm or technical error. The evidence for ITA graft performance in the non-LAD position also remains unconvincing.

The New Era: CABG without CPB and the Trend Towards MICS

The initial work in myocardial revascularization, done in an era prior to CPB, is credited to Vineberg who in 1946 began implanting ITAs into myocardium. In 1962 Sabiston conducted the first CABG without CPB and in 1964 Kolossov performed the first beating heart LITA-LAD anastomosis. Many of these techniques were described before CPB was refined and popularized. Several reports in the years that followed demonstrated the safety of off-pump bypass. However, advances in CPB technology and cardioplegia allowed surgeons to operate with greater precision and control. As a result, beating heart surgery was abandoned.

While CABG with CPB became the gold standard for coronary revascularization used in most centers around the world, reports over the last two decades regarding hematologic, metabolic, pulmonary, cardiac, and cognitive dysfunction resulting from CPB, have brought about the resurgence of CABG without CPB for treating ischemic heart disease. Driven by academic, clinical, and economic interests, work in less invasive approaches to CABG and surgical anastomosis of the LITA to LAD and other vessels has gained tremendous momentum over the past few years. Currently, beating heart surgery is practiced by a large number of surgeons in anywhere from 10-90% of their patients. Benetti, Buffalo, and Pfister repopularized off-pump coronary revascularization after reporting large trials between 1978-1992. Benetti’s report on his initial experience with beating heart surgery through an anterior thoracotomy indicated low morbidity and mortality rates comparable to conventional CANG. Pfister concluded that off-pump CABG is at least as safe as, if not more-so, than CPB in certain patient populations. More recently, Buffalo and colleagues reported an update on their experience from 1981 to 1994. They concluded that CABG without CPB has advantages of lower mortality and morbidity, less need for homologous blood, lower cost, and less hospitalization time. However, disadvantages included restriction of its use to a select group of patients, increased technical demand, and likely lesser reproducibility of results from one center to another based on surgeon’s skill. Despite encouraging results, these and other reports of off-pump bypass have been met with concerns of technical limitations and efficacy of the anastomoses. With the gold standard for safety and efficacy of surgical coronary revascularization still involving the use of CPB, off-pump techniques have been relegated to a small group of highly-skilled surgeons.

Much of the early work of Benetti and colleagues regarding beating heart surgery was inspired by the difficulties maintaining CPB and its supportive technology in lesser developed regions. While leading to innovative techniques and refinement of skill level, experience in off-pump CABG via median sternotomy led to the observations of benefit in patient recovery and, subsequently, consideration of less traumatic incisions. In 1994, Benetti demonstrated ITA harvesting using a small (8 cm) anterior thoracotomy. This procedure, known as minimally invasive direct coronary artery bypass (MIDCAB), was first brought to the attention of the mainstream cardiology community in 1995 by Subramanian and colleagues. They reported a reduction in post-operative pain and other complications usually seen with CPB and sternotomy, as well as a reduction in operative and hospital costs. Del Rizzo and colleagues reported similar results with decreased mortality along with a reduction in resource utilization (intensive care unit stay and post-operative hospital stay) in high-risk patients.

The use of new techniques that offer potential advantages for patients over conventional CABG is increasing. One of these approaches is port-access technology. Released in the fall of 1996, port-access technology utilized a peripherally based perfusion platform (femoral arterial and venous access for CPB) with ascending aortic balloon occlusion using a transfemoral endoaortic occlusion catheter. This system has many potential advantages over routine median sternotomy coronary revascularization in patients with serious co-morbid conditions. However, the potential risks and benefits of widespread application has not yet been quantified and further studies to better delineate the patient populations where this technique will offer the greatest advantages are still required.

For the most part, the MIDCAB procedure is limited by single-vessel disease, usually that of the LAD, yet some experience with bypass of the diagonal, intermediate branches of the left coronary artery and the right coronary artery exist. MIDCAB is therefore only applicable to a very small number of patients with ischemic heart disease (5-10% of the population with coronary artery disease) and limited to cases that require revascularization of one or
two anterior vessels. Consequently, incisions have been progressively lengthened to gain exposure to all coronary territories including, more specifically, the difficult to access posterior arteries. Rapid progression to off-pump coronary artery bypass (OPCAB) for multi-vessel revascularization has evolved due to the refinement of proper stabilization devices permitting unhindered surgical access to all coronary territories and significantly reducing postoperative morbidity and cost even in the elderly population.

The ultimate goal of MICS is progress beyond MIDCAB and OPCAB surgery and towards performing coronary anastomoses entirely endoscopically. Once again, these procedures are aimed at further reducing patient morbidity, length of hospital stay, and overall costs. Boehm and colleagues first reported the use of telemanipulation in humans to provide the surgeon with tools to perform totally endoscopic coronary bypass by allowing several degrees of freedom of motion. Boehm used this technology to perform a completely endoscopic anastomosis of the LITA to LAD on both an arrested and beating heart. The combination of robotics and 3-D visualization creates the necessary platform to overcome many of the limitations of the MIDCAB approach and earlier attempts at robotic surgery, which include awkward instrument handling, limited space which limits endoscopic manipulation, and unfavourable ergonomics for the surgeon. The surgeon can now operate in an ergonomically favourable position, using telemanipulated instruments, obviating any natural tremor, and increasing dexterity and precision. When combined with 3-D vision, the system creates depth perception and increases speed and safety. Robotic coronary bypass surgery may become a widespread reality in the near future. However, extreme costs, a steep learning curve, and a limited knowledge of the patient population that can most benefit from this procedure are all obstacles that must be overcome.

Future Directions

The future looks promising in the treatment of ischemic heart disease from a medical and surgical perspective. For the surgical patient, advances in surgical devices will hopefully lead to improvements in patient outcome with decreased morbidity. Recently introduced vascular stapling devices, which remove anastomotic variability (inter- and intra-surgeon), should lead to reduced operating room times and therefore diminished costs. Their use may lead the way to percutaneous CABG, which has already been performed in the experimental laboratory.

Furthermore, with recent advances in angiogenesis a whole new field of possibility for patients with advanced coronary artery disease not amenable to CABG or medical therapy is upon us. Trials are already underway in injecting vascular endothelial growth factor (a potent angiogenesis inductor) in regions of underperfused myocardium to try and promote angiogenesis and collateral circulation. Combining this technique with the Vineberg procedure may provide another treatment option.

Conclusion

Though an exciting era in cardiac surgery is well underway, caution must be taken as we proceed forward by careful validation of new methods. Minimally invasive procedures may have advantages to the patients such as reduced recovery time, more rapid return to normal activities of daily living, reduced hospital stay, decreased costs on both a short-term and long-term basis, and ultimately improved quality of life. Well designed, randomized, prospective trials comparing proven methods with new techniques for both short- and long-term outcomes is mandatory to support the claims and intentions described above. Furthermore, we need to determine which patient populations will realize substantial advantages from surgery without CPB and which surgical intervention will be of most benefit. Ongoing research will hopefully extend the procedural possibilities to include better myocardial protection, access to more regions of the heart, and, ultimately, a wider patient selection.

References
