UPDATE

Myocardial Revascularization (VIII)

Coronary Surgery. Developments in the Last Decade. Indications and Results

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Coronary artery bypass surgery is endorsed by the excellent, well-documented, long-term results that follow complete revascularization and the use of 1 or 2 mammary artery grafts. This article contains a review of the current indications for and the results of such surgery and an evaluation of new challenges and opportunities, including the implementation of safer and less aggressive surgery, and surgery associated with other operative procedures. The aim was to develop a strategy linked to a cycle of innovation that could be used to adapt surgery to the needs of the population, to new technologies, and to pioneering developments.

Key words: *Coronary artery bypass surgery. Off-pump coronary artery bypass surgery. Internal mammary artery. Ischemic mitral regurgitation. Mitral restrictive annuloplasty. Surgical ventricular reconstruction.*

Cirugía coronaria. Evolución en la última década. Indicaciones y resultados actuales

La cirugía coronaria está avalada por unos excelentes resultados, bien documentados a largo plazo como consecuencia de la revascularización completa y la utilización de una o 2 arterias mamarias. En este artículo se revisan los resultados y las indicaciones de la cirugía y se valoran los nuevos retos y las oportunidades que incluyen la cirugía más segura, menos agresiva y asociada a otros procedimientos quirúrgicos. El objetivo es desarrollar estrategias ligadas a un ciclo innovador que adapte la cirugía a las necesidades de la población, las nuevas tecnologías y a las actividades pioneras.

Palabras clave: *Cirugía coronaria. Cirugía coronaria sin bomba. Mamaria interna. Insuficiencia mitral isquémica. Anuloplastia mitral restrictiva. Reconstrucción ventricular.*

INTRODUCTION

The origin of coronary artery bypass surgery is uncertain and depends on geographical location and the preferences of the author: Senning in Europe (1966), Garrett (1966) and Favaloro (1967) in the USA, or even much earlier if we include the experimental work of Alexis Carrel. Following the attempts made by Vineberg in Montreal from 1951 onwards to implant the internal mammary artery (IMA) into the myocardium, other proposals were made for direct revascularization by endarterectomy or interposition grafts using the saphenous vein or IMA. However, these techniques were neither accepted nor their potential use evaluated.[1] In 1964, Kolesov, from Leningrad, anastomosed the IMA to the left anterior descending (LAD) artery.[2] Without knowledge of this contribution, Garrett, from the group of deBakey in Houston, used the saphenous vein to revascularize the LAD artery in 1966, the graft remaining patent at 7 years,[3] and Favaloro introduced the aortocoronary bypass in the Cleveland Clinic in 1967,[4] with 741 cases treated in 1971.[5] In 1968 Green,[6] in New York, anastomosed the IMA to the LAD artery; in 1971, Flemma, Johnson, and Lepley in Milwaukee described the advantages of sequential bypass grafts[7]; bilateral IMA grafts are known to have been in use in 1972 but may have been employed as early as 1968.[8] Over a period of 6 years, coronary artery bypass surgery established its

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foundations and became universally accepted as a valid treatment.

Coronary artery bypass surgery is one of the best forms of treatment and its short-, medium-, and long-term results are well documented, situating it at the forefront of scientific knowledge.[9] The number of surgical interventions of this type performed in the USA increased significantly in the period up to 1996 but has decreased progressively since the year 2000, with a reduction of 100 000 cases per year.[10] This change is the result of the introduction of the stent in 1996, the use of which overtook the number of surgical interventions in 1998. An annual reduction of 7% to 10% in the number of surgical interventions has occurred in Europe, and in Spain the number fell by 16% between 2000 and 2002.[11] This reduction contrasts with the increase in the number of percutaneous coronary interventions (PCI), currently around 15% annually.[12,13] Advances in PCI, including the use of drug-eluting stents, have had an impact on the global reduction in the number of surgical interventions.[14,15] However, although drug-eluting stents have been shown to be more effective in certain patient groups, long-term scientific evidence is lacking, as is data from other types of patients or lesions.[16] These changes mean that surgical treatment of ischemic heart disease must adapt to future demands. Thus, this article will review the results of and indications for surgical intervention, and assess new opportunities, including safer, less invasive surgery and intervention associated with other surgical procedures.

RESULTS. INDICATIONS

Results

Mortality

Coronary artery bypass surgery represents the surgical technique with probably the best-documented short-, medium-, and long-term results. In-hospital mortality in the USA and Europe is less than 2.5%.[17-19] Patient survival following surgery is approximately 98% at 1 month and 97%, 92%, 81%, and 66% at 1, 5, 10, and 15 years, respectively.[20] The shape of this survival curve, with an initial reduction in patient survival during the first few months followed by a plateau up to 5 years and a progressive reduction in survival from that point on, more apparent from the eighth year onwards, is associated with occlusion of bypass grafts, disease progression, and development of comorbid conditions. The use of artery grafts for revascularization improves this survival curve.[21,22]

Large databases have been used to develop risk stratification models to predict mortality and outcome.[18-20,22-24] All of the scales include the following variables as predictors of in-hospital mortality: age, female sex, repeat revascularization, procedure urgency, left ventricular dysfunction, noncoronary surgery, kidney failure, and symptomatic peripheral artery disease. Other, anatomical factors must be added to this list, including incomplete revascularization, proportion of small caliber distal vessels, associated endarterectomy, severe left main artery disease, and experience of the surgeon.[20] Table 1 shows the EuroSCORE scale for prediction of surgical risk, developed using data from 19 030 patients who underwent surgery in Europe between September and December 1995.

Outcome

The probability of remaining free from angina at 1, 5, 10, 15, and 20 years following surgery is 95%, 82%, 61%, 38%, and 21%, respectively.[25] These results show that in the long term angina is almost inevitable, while the mean length of time to its appearance following surgery is slightly more than 12 years. The use of the IMA to revascularize the LAD artery reduces the recurrence of angina, this effect being most apparent beyond 4 years after surgery.[26] The probability of remaining free from infarction at 30 days and 5, 10, 15, and 20 years following surgery is 97%, 94%, 86%, 73%, and 56%, respectively.[26] The probability of sudden death is low, 97% of patients remaining unaffected

TABLE 1. **EuroSCORE Prediction of Surgical Risk**[19]

Risk Factors	Points
Age (each 5 years from 60 years)	1
Female gender	1
Chronic pulmonary disease	1
Peripheral artery disease	2
Repeat surgery	3
Renal failure	2
Active endocarditis	3
Critical preoperative state	3
Unstable angina	2
Ejection fraction less than 0.30	3
Recent myocardial infarction	2
Pulmonary hypertension	2
Emergency	2
Noncoronary surgery	2
Surgery of the thoracic aorta	3
Interventricular communication following myocardial infarction	4
EuroSCORE Index, Points	**Estimated Mortality, %**
0-2	1-0
3-5	2.62-3.51
6-8	6.51-8.37
9-10	14.0-19.0
11-13	31.0-42.0
≥13	>42.0

at 10-year follow-up. Severe left ventricular dysfunction is the main risk factor associated with sudden death: while the risk is low in patients with an ejection fraction (EF) of more than 0.55, it reaches 15% at 15-year follow-up in those patients with an EF of less than 0.25. The use of implantable cardiac defibrillators in this group of patients with severe ventricular dysfunction does not improve survival.[27] Coronary artery bypass surgery does not reduce the frequency or severity of ventricular arrhythmias in the majority of patients,[28] since these arrhythmias are more closely linked to ventricular scarring than areas of ischemia. Nevertheless, a subgroup of patients without ventricular scarring or aneurysm, whose arrhythmias are secondary to ischemia, does show improvement following surgery. Atrial fibrillation has a negative impact on long-term survival following surgery[20] and is a frequent complication in the immediate postoperative period in 23% to 33% of patients who undergo surgery with extracorporeal circulation (ECC).[29,30]

Recovery of maximum functional capacity is directly related to preoperative ejection fraction and extent of revascularization.[31] Although quality of life improves up to values close to those of the general population, around 25% of patients only achieve suboptimal values.[32] Preoperative quality of life, female sex, age, and chronic heart disease represent factors that have a negative impact on postoperative quality of life.[32]

Repeat Revascularization

The probability that percutaneous or surgical repeat revascularization is not required at 30 days, and 5, 10, 15, and 20 years is 99.7%, 97%, 89%, 72%, and 48%, respectively.[33] The most common reason for repeat revascularization is vein graft atherosclerosis followed by disease progression in the native artery.[34] Although the use of the IMA did not lead to a significant reduction in the rate of repeat intervention in the study of Sergeant et al,[33] the experience of the majority of groups shows that the use of the IMA to revascularize the LAD artery reduces the requirement for repeat revascularization and increases the interval between the first and, where required, second intervention.[35,36] Bilateral IMA grafts reduce the requirement for repeat revascularization even further.[22,35-37]

The risk of reintervention is twice that of a first intervention[33,34] and is more associated with the higher prevalence of risk factors than with the surgical technique itself.[34,38] The factors that have a negative influence on early and late survival are severe left main artery disease or 3-vessel disease, age, and severe left ventricular dysfunction.[22,38] PCI is increasingly used in patients who are symptomatic following coronary artery bypass surgery.[34] The results for treatment of vein bypass grafts are significantly better with stents than with balloon angioplasty in terms of efficacy, lumen diameter, survival, myocardial infarction, and requirement for repeat revascularization.[39] PCI in protected left main coronary arteries with intravascular ultrasound guidance is a genuine alternative to repeat surgical revascularization.[40]

Type of Bypass Graft

Historically, the most commonly used graft has been the saphenous vein. Following implantation, the graft displays intimal hyperplasia that is not progressive and is inversely proportional to the flow in the graft, the caliber of the graft approaching that of the native vessel in what is considered to be a process of remodeling. The development of atherosclerosis with plaques, ulcers, and thrombosis is of particular importance; management of risk factors and aggressive treatment with antiplatelet drugs and statins improves or delays these changes.[41] During the first year following surgery, 20% of bypass grafts present stenosis of the proximal anastomosis with occlusion of 25% of these grafts within the first 5 years; although in 50% of bypass grafts some degree of stenosis can be observed in the distal anastomosis, in the majority of cases it does not progress. In mixed groups of patients, the patency of the vein bypass graft is 90% at 1 month and 50%, 30%, and 20% at 10, 15, and 20 years, respectively.[35,41] However, patency of a saphenous vein graft anastomosed to the LAD artery is 80% at 10 years.[35]

Although the superiority of the IMA has been demonstrated since 1973, its use was not widely accepted until the mid 1980s. Use of the IMA reduces recurrence of angina, rate of myocardial infarction in the medium term, requirement for repeat revascularization, and the interval between first and second surgical intervention.[25,26,35] Patency of an in situ left IMA used to revascularize the LAD artery is 95% and 90% at 10 and 15 years, respectively.[22,33,35,36] Stenosis is present in 5% to 10% of patent bypass grafts; however, the majority of cases do not progress as far as occlusion. The low thrombotic threshold velocity, resistance to the development of atherosclerosis, release of vascular endothelial growth factor and prostacyclin, and reactivity to vasodilators explain its high patency and status as an ideal bypass graft.[35,36,41,42]

A factor that influences the high patency of the IMA is the revascularization of the LAD artery. The use of the IMA to revascularize arteries other than the LAD, arteries with less than 60% stenosis, or the use of the right IMA as an aortocoronary bypass graft instead of an in situ graft reduces the patency of the IMA graft; here, the results are similar to those obtained with saphenous vein grafts.[41-43] The adequate flow reserve with the right IMA anastomosed to the left IMA as a Y graft is confirmed by excellent clinical results for flow and patency.[44,45] Lengthening of the bypass graft is also a safe technique with a patency of greater than 95%,[46] as is also true of sequential anastomosis, except when revascularization is undertaken in marginal branches of the circumflex artery or distal branches of the right coronary artery.[47] The use of bilateral IMA grafts, without increasing in-hospital mortality, improves long-term survival and reduces the requirement for repeat revascularization[22,36,37,41,45]; these differences favoring the use of bilateral IMA grafts are more pronounced during the first 10 years following the intervention in patients of advanced age who present multiple risk factors than in young patients.[41] Reticence over the use of bilateral IMA grafts in diabetic patients has been resolved with the dissection of *skeletonized* IMA.[48] Diabetic patients receive the most benefit from the use of bilateral IMA grafts, displaying improved survival and a reduction in the rate of myocardial infarction and the requirement for repeat revascularization.[36] These results recommend complete coronary revascularization with double IMA grafts in diabetic patients and those patients who have a life expectancy of greater than 10 years or multiple associated risk factors.[49]

The superiority of the IMA over the saphenous vein led to reintroduction of the use of the radial artery in 1992 following its abandonment during the 1970s. Its use has been extended in combination with the IMA, as an aortocoronary bypass graft, simple or sequential, as a Y graft or as an extension of the IMA.[50] The results published show a patency similar to the right IMA in the medium term and similar to the left IMA in the short term, with 95% of grafts remaining patent at 5-year follow-up.[50] However, its use has been in rapid decline since 2004 due to the recurrence of angina caused by spasm and the publication of results indicating that medium-term patency is lower than with IMA or saphenous vein grafts, with a percentage of occlusion or severe stenosis of 51% at 2 years and a requirement for percutaneous or surgical repeat revascularization in 27% of patients.[51] The use of the gastroepiploic and inferior epigastric arteries is also declining as a result of angina recurrence due to the difference in caliber between the graft and the coronary artery, and an estimated patency of 80% and 62% at 5 and 10 years, respectively.[52,53]

Indications

Indication for surgery requires a comparative study of the benefit over medical treatment and PCI. The complexity of this apparently simple proposal centers on the fact that the comparative benefit of surgery may depend on the circumstances. The predictions and comparisons must be precise and, to this end, an enormous volume of information is available that allows the most efficient treatment to be proposed to each patient. Coronary lesions and risk factors are highly variable and recommendations based on studies performed with heterogeneous patient populations are of limited value. The general indications from the 1999 guidelines of the American College of Cardiology and the American Heart Association, updated in 2004,[54] are shown in Table 2, based on the summary of Alonso Martín et al.[13]

Surgery or PCI is not indicated per se in patients with stable ischemic heart disease, with mild or moderate angina, confirmed by limited reversible changes in tests for the detection of ischemia. PCI—if the anatomy is favorable—or surgery are indicated for treatment of severe angina. Surgery clearly improves the prognosis of left main coronary artery stenosis and it is a priority or urgent indication, depending on the severity of the stenosis or symptoms[55]; nevertheless, PCI has recently been successfully employed in selected cases.[40,56,57] Surgical intervention improves survival in patients with 3-vessel disease and low EF[58] or normal EF[59], although with lower statistical significance in the latter case. PCI is effective in many patients with 2-vessel disease; the prognosis with medical treatment is generally better than in 3-vessel disease and surgical intervention is not indicated in the majority of cases. However, surgical intervention is indicated in lesions equivalent to left main coronary artery lesions, in severe proximal lesions of the LAD artery, when the ejection fraction is low, or when there is a large area of viable myocardium and the patient is at high risk.[59] Indication for surgery in single-vessel disease is rare since the results of medical treatment and PCI are good. IMA bypass grafts to the LAD artery are an appropriate option for patients with a proximal lesion of the LAD artery and evidence of extensive ischemia or low EF. According to the Spanish Society of Cardiology, indication for surgery in acute coronary syndrome without ST-segment elevation is dependent on the results of coronary angiography performed in patients at high or moderate risk.[13]

Although surgery improves prognosis in patients with left ventricular dysfunction, the risk and benefits are not clear in patients with an EF of less than 0.30. In the 1970s and 1980s, in-hospital mortality varied around 10%, with values ranging from 2.9% to 39% according to the presence or absence of pulmonary hypertension, heart failure, ventricular arrhythmias, and preoperative viability assessment.[60] Improvements in anesthesia and monitoring techniques, myocardial protection by cardioplegia, and off-pump coronary artery bypass surgery, as well as the improvement of techniques for the quantification of ischemia and viability, allow an in-hospital mortality of less than 3% following surgical intervention in patients with evidence of hibernating myocardium.[61,62] In areas without the potential for functional recuperation, less adaptation with less pronounced myocardial cell hypertrophy, greater destruction of

TABLE 2. **Indications for Coronary Artery Bypass Surgery[54] (ACC/AHA)***

Class I
Asymptomatic patients or patients with mild angina
Significant stenosis of the left main coronary artery (≥50%) or equivalent (≥70% in the LAD artery and proximal Cx artery; evidence level A)
Significant disease in 3 vessels. Greater benefit is obtained with an EF of less than 0.50 and/or large areas of ischemia (evidence level C, or if angina is stable, evidence level A)
Stable angina
As above (asymptomatic patients and patients with mild angina)
Significant disease in 2 vessels: *a)* proximal LAD artery and/or EF less than 0.50 or demonstrable ischemia (evidence level A); *b)* no disease of the LAD artery but with high risk criteria and extensive viable myocardium (evidence level B)
Incapacitating stable angina with acceptable risk for surgery (evidence level B)
Unstable angina or AMI
Unstable angina or non-Q wave AMI with significant left main artery disease or equivalent (evidence level A)
Unstable angina or AMI without the possibility of PCI and progressive ischemia that does not respond to nonsurgical treatment
Class II
Asymptomatic patients or patients with stable angina
Proximal LAD artery disease and disease of 1 or 2 vessels (class IIa). If the EF is less than 0.50 or there is extensive ischemia it is a class I indication (evidence level A)
Disease of 1 or 2 vessels without disease of the proximal LAD artery (class IIb). If criteria for high risk are met and there is a moderate or extensive area of viable myocardium then it is a class IIa indication (evidence level B)
Unstable angina or non-Q wave AMI
Proximal disease of the LAD artery and disease of 1 or 2 vessels (class IIa, evidence level A)
Disease of 1 or 2 vessels without lesion of the proximal LAD artery if PCI is not possible (class IIb, level B evidence)
Class III
Stable angina with coronary artery stenosis of less than 50% (evidence level B) or with 50% to 60% stenosis without involvement of the left main coronary artery and no demonstrable ischemia (evidence level B), or with disease of 1 or 2 vessels without disease of the proximal LAD artery and no evidence of ischemia or a small area of viable myocardium (evidence level B)

*ACC indicates American College of Cardiology; AHA, American Heart Association; LAD, left anterior descending; Cx, circumflex; EF, ejection fraction; AMI, acute myocardial infarction; PCI, percutaneous coronary intervention.

myocardial architecture, and enhanced expression of antiapoptotic genes have recently been described. These findings suggest that endomyocardial biopsy should be performed to indicate coronary artery bypass surgery or heart transplant in patients with unfavorable results of viability assessments.[61]

Indications: Surgery Versus Percutaneous Coronary Intervention

The choice between surgery and PCI in multivessel disease is affected by the following considerations: *a)* the choice between the 2 techniques will only be possible in a subgroup of patients in whom it would be possible to perform more or less complete revascularization with PCI.[13] Coronary artery bypass surgery can be performed in small-caliber arteries and in the study of Levin et al[63] bypass grafts could be successfully implanted in 73% of vessels considered inadequate in coronary angiography due to small distal caliber or absence of filling; *b)* if the risk associated with the procedure is similar, although the rate of restenosis and the requirement for repeat revascularization is greater following PCI, and irrespective of cost analyses, it is clear that the patient and cardiologist will accept PCI because it will always be less aggressive and it can be repeated indefinitely.

The results of 9 randomized trials comparing percutaneous and surgical intervention were published during the 1990s; their conclusions were the subject of a joint document published by the American College of Cardiology and the American Heart Association.[64] The results of these studies revealed significant differences in favor of surgery in terms of the recurrence of angina and the requirement for repeat revascularization, without differences in mortality, with the exception of the BARI trial, in which survival of diabetic patients at 7 years was improved following surgery.[13,64,65] These results have been corroborated by the ARTS,[66] SoS,[67] and SIMA[68] trials. The development of drug-eluting stents may reduce or eliminate the advantages of surgery in terms of the requirement for repeat revascularization.[14-16] This suggestion is supported by the initial results of the ARTS II trial,[13] while the preliminary results of the Syntax trial[69] have yet to be released.

WHERE ARE WE AND WHERE ARE WE GOING: NEW CHALLENGES AND OPPORTUNITIES

While most surgeons assumed that the future would be like the past, the golden age of an industry is not a guarantee of long-term survival. The future is linked to a process of innovation that will adapt surgery to the needs of the population, to new technologies, and to pioneering developments. Success will depend upon the innovative attitude of surgeons, the support of the health industry and management, and in particular, it will depend on the patients.

Progress and New Technology

The development of heart surgery has been accompanied by various technological improvements, thanks to which surgery is now supported by improved guarantees. Although many have tried to play down the true value of ECC, its introduction opened the door to a host of therapeutic possibilities.

Technical Progress

Nowadays, patients who undergo surgery have more severe and diffuse coronary artery lesions, a greater proportion have ventricular dysfunction and comorbid conditions, and the number of repeat revascularization procedures has increased. The increase in the estimated risk of death[18,19,23] is accompanied by a reduction in the mortality that is actually observed. This paradox is due to the fact that risk stratification models overestimate mortality because patients who died when the stratifications were developed now survive. Furthermore, a subgroup of 5% to 6% remains in intensive care for prolonged periods leading to increased costs. Improved surgical safety has been achieved through increasing experience, greater understanding of biochemistry, physiology, and pathophysiology, the parallel developments in other fields, and complementary technological progress.

– *Diagnostic and monitoring techniques*. Failure occurs in heart surgery as a result of technical problems or lack of information. Better preoperative information improves the indication and offers more precise information regarding the risk and benefit of surgery. Notable in relation to coronary artery bypass surgery are the technological developments for assessment of myocardial viability using echocardiography, gated single photon emission computed tomography (SPECT), positron emission tomography and magnetic resonance imaging of the heart, providing information on contractile reserve, myocardial microperfusion, cellular integrity, and cell metabolism.[70] Intraoperative monitoring offers more precise information on hemodynamic status and homeostasis, through the use of new Swan-Ganz catheters, echocardiography, improved analytical equipment, and the technical developments in the monitoring and safety of ECC pumps. Ultrasound measurement of flow in bypass grafts is obligatory during surgery, especially in off-pump surgery, in order to quantify flow, flow reserve, and pulsatility index, and thereby assess the quality of the anastamosis.[71] Follow-up with multislice computed tomography (CT) has been addressed in numerous studies and a sensitivity of 86% to 97% with a specificity of 89% to 100% has been observed for the assessment of bypass graft occlusion.[72,73] Intraoperative measurement of flow and follow-up with multislice CT represent 2 excellent tools for use in comparative studies of coronary artery bypass surgery techniques.

– *Myocardial protection*. The incorporation of cardioplegia at the end of the 1970s changed the development of heart surgery. Improvements in myocardial protection have facilitated surgical intervention in patients with left ventricular dysfunction, with excellent results. However, this problem cannot be considered resolved. Cardiac causes are responsible for 65% of postoperative deaths and defective myocardial protection plays a significant role. Intraoperative myocardial lesions, revealed by increased enzyme levels, infarct, or low cardiac output, have a negative impact on long-term survival.[74] There are demonstrated principles that should be observed: *a)* maintenance of normothermia or slight hypothermia in ECC. Hypothermia below 32°C has no benefit and is potentially damaging; *b)* blood cardioplegia is superior to crystalloid cardioplegia; *c)* the impact of ECC on myocardial protection, with the liberation of inflammatory mediators with negative inotropic effects. Controversial techniques that have shown similar results can be added to these principles: warm cardioplegia or cardioplegia at 4°C, continuous or discontinuous anterograde or retrograde perfusion.[74] Various proposals that were initially received with enthusiasm, such as addition of L-arginine, antioxidants, insulin, sodium-proton exchange inhibitors, leukocyte filters, or ischemic preconditioning, have not been clinically confirmed.[74,75] Various alternatives are currently awaiting clinical results, such as the use of esmolol or monoclonal antibody complement inhibitors as adjuncts to cardioplegia.[74]

– *Anesthesia and patient care.* Fast track is a specific form of intraoperative management that leads to improved postoperative recovery, reducing the need for cardiac and respiratory support and intensive care. The intraoperative management can be divided into 4 components: brain, temperature, peripheral vascular tone, and meticulous patient care. New faster acting anesthetics make the development of this strategy much easier and thoracic epidural anesthesia facilitates immediate extubation, offers better cardiac and pulmonary protection, and reduces postoperative pain.[76] Safety has been improved with the arrival of new inotropic drugs such as levosimendan and awareness of the cardioprotective benefits of isoflurane and thyroid hormone. Autotransfusion techniques, blood conservation, improved understanding of homeostasis, the use of antifibrinolytics, and off-pump surgery, has reduced the consumption of blood products. These improvements have led to the recent development of outpatient cardiac surgery.[77] To obtain the benefit hoped for with these improvements, an active process is necessary that requires specific intraoperative management.

Less Invasive Surgery

Progress in anesthesia has been complemented by the development of less invasive surgical techniques, as a result of a willingness to invest on the part of the health industry. Minimally invasive coronary artery bypass surgery is equivalent to off-pump surgery and can be undertaken via small incisions or median sternotomy:

– *Access through minimal incisions*. The development of minimally invasive direct coronary artery bypass surgery (MIDCAB) was accompanied by the invention of a confusing number of incisions in the 1990s—"S," "L," "J," "C," "T," etc. Currently, indications are limited to a small number of cases of revascularization with an IMA graft in single lesions of the LAD artery, approached by left minimal thoracotomy or lower ministernotomy, or to revascularization of the posterior descending artery with a gastroepiploic artery bypass graft approached by subxiphoid incision.[78] Hybrid revascularization, based on the demonstration that the strongest determinant of long-term survival is revascularization of the LAD artery with an IMA bypass graft, consists of a combination of an IMA to LAD bypass graft and PCI in the remaining lesions. The evidence that surgical invasiveness is mainly linked to the use of ECC limits its indications to patients with a high probability of subsequent surgery: those with the most critical lesions of the LAD artery, the remaining arteries treatable by PCI, and who are at high risk, and in cases of severe lesions of the left main coronary artery in high-risk patients.

– *Off-pump coronary artery bypass surgery by sternotomy*. The invasiveness of coronary artery bypass surgery is associated with the use of ECC rather than the size of the incision. This finding, along with the importance of the complete revascularization that can be obtained by median sternotomy without ECC, through the use of coronary stabilizers, has turned attention towards off-pump coronary artery bypass surgery with complete revascularization via median sternotomy, known in the English-language literature as off-pump coronary artery bypass surgery (OPCAB). OPCAB reduces, although does not abolish, the levels of circulating inflammatory mediators,[74] and the elimination of aortic clamping reduces myocardial stress. Although the clinical results have not yet reached evidence level I, the results of large observational studies indicate benefits of this technique in terms of short-term and long-term survival—mainly in patients with ventricular dysfunction, diabetics, and elderly patients[79-81]—the incidence of myocardial infarction and cerebrovascular accident,[82] and the incidence of postoperative atrial fibrillation.[83] Off-pump surgery with artery grafts, associated with thoracic epidural anesthesia and fast-track management currently represents the gold standard in coronary artery bypass surgery. Although it currently accounts for approximately 25% of coronary artery bypass surgery in Europe, its use will increase as a result of technical improvements that aid anastomosis[84] and with increased training of surgeons. Coronary artery bypass surgery with minimal closed-circuit ECC is a new approach that has an intermediate invasiveness between surgery with conventional ECC and off-pump surgery. However, the fact that teams who have converted to off-pump surgery now use it for 90% of all isolated coronary artery bypass surgery performed casts doubt on the usefulness of minimal closed-circuit ECC surgery.[9]

– *Endoscopic and robotic surgery*. Endoscopic surgery using conventional instruments is limited by the imprecision of the sutures due to 2-dimensional visualization, and its use has been restricted to dissection of the IMA or saphenous vein. Robotic surgery with remote computer-assisted manipulation and 3-dimensional visualization is in the initial stages of clinical application.[86]

Associated Surgery

The increasing age of the population in which coronary artery bypass surgery is performed has lead to an increase in its association with other procedures:

– *Cardiac valve surgery*. In the STS-database, 48.2% of the cardiac valve surgery performed in the USA between 1992 and 2001 was associated with coronary artery bypass surgery.[18]

The majority of patients in whom coronary artery bypass surgery is performed alongside aortic valve replacement have degenerative stenosis and are more than 65 years old. In this group, the decision to take an aggressive approach to moderate aortic stenosis is more aggressive because tolerance of repeat operation is reduced and the bioprostheses used display excellent durability in this age group.[87]

Ischemic mitral regurgitation is associated with increased mortality that is directly related to the degree of regurgitation,[88] while isolated coronary artery bypass surgery does not correct mitral regurgitation.[89] All 3 functional types of mitral valve regurgitation, according to the Carpentier classification, can coexist in ischemic heart disease. Restriction of valve opening (type IIIb) secondary to ventricular akinesia or dyskinesia increases the distance between the papillary muscles and the mitral ring, and the excessive traction on the chords prevents the coaptation of the valves; slight or moderate dilation of the ring (type I) is often associated; and valve prolapse (type II) is present in a third of cases.[90] Restrictive mitral annuloplasty associated with coronary artery bypass surgery has an in-hospital mortality of 5% in patients with an EF of less than 0.35 and a survival at 2 years of 84%, with significant improvement of ventricular volumes.[91]

– *Ventricular remodeling*. Left ventricular remodeling after infarction is a complex phenomenon and although early percutaneous intervention protects the subepicardium, it is less successful in the recuperation of the subendocardium. Around 30% of patients successfully treated by PCI display an increase of more than 20% in the left ventricular diastolic volume at 6 months.[92] Nonrandomized studies that have compared the results of medical and surgical treatment in patients with ventricular dysfunction and heart failure suggest a balance in favor of surgery.[92] However, for surgical treatment to be effective, the following factors must be taken into account: complete revascularization, reduction of ventricular volume at the expense of the interventricular septum, and restoration of ventricular geometry to recover its elliptical shape.[92] If the results of the STICH trial confirm expectations, surgery for treatment of the sequelae of myocardial infarction will recover its former popularity.[93]

– *Surgery associated with atrial fibrillation*. Long-term survival following coronary artery bypass surgery is significantly lower in patients with chronic atrial fibrillation[20] and the prevalence of postoperative atrial fibrillation is a limiting factor in the development of outpatient surgery.[77] The development of bipolar electrode catheters has simplified epicardial radiofrequency ablation, improved transmurality, and eliminated the possibility of esophageal perforation. Thus, ablation can extend the indications for associated coronary artery bypass surgery in the small percentage of patients undergoing surgery in atrial fibrillation or as a preventative associated treatment with surgery that is less aggressive in the short term.

CONCLUSIONS

Coronary artery bypass surgery is endorsed by the excellent, well-documented long-term results generated with complete revascularization and the use of 1 or 2 IMA grafts. Surgical invasiveness has been reduced by off-pump surgery, the use of thoracic epidural anesthesia, and the introduction of outpatient surgery. The progressive reduction in the use of surgery in favor of percutaneous intervention demands strategies linked to innovation that adapts surgery to the needs of the population, new technology, and pioneering developments. Success will depend upon the attitude of the surgeons, the support and investment from industry and health management, and in particular, it will depend on the patients.

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