Honored Guest Lecture

Coronary artery surgery: the end of the beginning

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Abstract

In each of the first three decades of myocardial revascularization, conventional treatment has been revised completely. This lecture comments on three areas of discovery that have shaped the evolution of myocardial revascularization: science, technology development, and revascularization. The discoveries in all three areas are inexorably interrelated. The single greatest lesson learned so far is that conduit performance carries more prognostic weight than any other factor. We have observed that vein graft atherosclerosis is predictable, and that the first-generation lipid lowering drugs have a favorable effect in patients who achieve marked LDL reduction. Biologically better revascularization begins with use of the internal thoracic artery for grafting to the anterior descending coronary artery. As the results of internal thoracic artery grafting are widely reported, arterial bypass revascularization has expanded, notably by radial and gastroepiploic arteries. The results of bilateral internal thoracic artery grafting are discussed, including large-scale registry results of internal thoracic artery usage in the United States. The internal thoracic artery is significantly underutilized. Diabetes affects both endoluminal and surgical revascularization. The new pharmacology in cardiology interventions shows promise in diminishing restenosis and thrombosis even in diabetic patients. Conversely, extended internal thoracic artery grafting may also benefit diabetic patients. Now we are entering a new age of minimally invasive coronary surgery. We have passed through the early stages of mini-thoracotony, and we are moving on to access through 1-cm ports, intrathoracic cannulation, antegrade and retrograde myocardial protection, and computer guided three-dimensional vision and instrumentation. The potential for robotic control adds greater precision, ease of use, and safety. This new technology will be integrated with diagnostic information, intraoperative monitoring, anesthesia and perfusion data, cost accounting, and surgical note transcription. The operating room of the future will package intraoperative information and is adaptable to all surgical specialties. The future of coronary artery surgery will depend on minimally invasive techniques, all-arterial grafting, and selective lipid modification to reduce progressive atherosclerosis. The conclusion of this decade marks the end of the beginning. The new generation of cardiothoracic surgeons will share in an array of technology and research unmatched in previous decades. © 1998 Elsevier Science B.V. All rights reserved

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1. Introduction

In the first three decades of coronary artery surgery, numerous interrelated discoveries have emerged in the science of atherosclerosis, in technology development and in revascularization. In each decade, conventional treatment has been revised completely. The next generation of coronary artery surgery will be distinguished by advanced pharmaceuticals for selective lipid lowering, plaque stabilization and treatment of acute coronary syndromes. Surgical revascularization may be complemented by neoangiogenesis, improving surgical and medical treatments of heart failure, routine use of all arterial grafts and the technologies of minimally invasive access. Later, unlocking the genome will allow creation of inhibitory drugs which block the formation of atherosclerosis.

The purpose of this lecture is to put this continuum of discovery in perspective and to preview the pace of change
that will affect coronary artery surgery. Since I was present near the creation of bypass surgery and continue to practice, I may qualify as an expert, which is defined as one who has made all the possible mistakes that can be made in a very narrow field [1].

2. Atherosclerosis

Apart from epidemiologic investigations, the entire science of atherosclerosis has developed in this initial era of myocardial revascularization (Table 1). Treatment has traditionally been aimed at an inert collection of cholesterol, fibrosis and calcium that grew unpredictably until it compromised or stopped arterial blood flow. Today, we know that atherosclerosis is multifactorial, dynamic, episodic and vulnerable to new therapies. In Table 1, 30 categories of advance are defined, all of which have occurred in the past three decades.

A great deal of scientific investigation has concentrated on an amazing single cell contiguous surface, the vascular endothelium, which undergoes phenotypic modulation in response to injury or activation. In basic terms, dysfunction of the endothelium is the loss of balance between relaxing and contracting factors, between procoagulant and anticoagulant mediators, and between growth inhibiting and growth promoting factors. Oxidation of low density lipoprotein (LDL) is considered the true perpetrator of atherosclerosis, and there is great variation in LDL resistance to oxidation from one person to the next. As LDL oxidizes, it becomes more negatively charged and the LDL receptor cannot recognize the new form, a different, non-regulated receptor, the scavenger receptor on macrophages binds and accepts LDL. The oxidized LDL molecule causes both toxic and proinflammatory effects [2,3]. Antioxidants ranging from the Mediterranean diet to vitamin E and probucol have been shown to make LDL more resistant to oxidation.

Oxidized LDL acts as a chemoattractant which contributes to the recruitment of circulating monocytes. Smooth muscle movement is promoted by platelet, endothelium and macrophage derived growth factors and, through phenotypic variations, smooth muscle cells contribute to matrix and foam cell formation. The macrophage is the principal inflammatory mediator in the atherosclerotic plaque. The highly cross-linked vascular extracellular matrix is the battleground where the atherosclerotic process occurs.

Coronary artery thrombosis is generally attributed to plaque rupture [4] or plaque erosion [5], the latter more frequent in women and younger persons. The great majority of fatal acute ischemic events occur in mild to moderately (<50%) narrowed arteries [6]. Plaque vulnerability to rupture is determined by inflammation, lipid core size, cap thickness, density of smooth muscle cells, and macrophage activity, not to severity of stenosis. In 1980, endothelial derived relaxing factor was discovered and the molecule was nitric oxide which prevents vasospasm and may contribute to coronary arterial remodeling wherein the artery enlarges as a response to plaque growth [7]. At approximately 40% narrowing, the artery appears incapable of further remodeling. Decreased production of nitric oxide or other endothelial-derived products may stop the remodeling process.

Epidemiologic investigations linked dietary fat to atherosclerosis and further studies demonstrated that reducing plasma cholesterol lowered the probability of coronary events.

The newer HMG-CoA reductase inhibitors lower serum cholesterol and LDL 25–60% or two to five times that of first generation trials with cholestyramine or diet alone. The latest statins have a greater effect on LDL with fewer side effects. Lipid lowering by statin therapy reduces the rate of myocardial infarction by more than 30% over 5 years and also benefits patients age 65 and older [8]. The reduction in cardiovascular events in old and younger patients is in part, attributable to plaque stability rather than a reduction in stenosis. In statin trials, the accompanying and unexplained lower stroke rate may be attributed to the same effect. Effective lipoprotein management has consistently resulted in less progressive atherosclerosis and an increase in documented regression. The major trials have shown that there was an average of 24% more progression and 20% less regression in the control group compared with statin therapy [9,10]. Patients with the largest LDL decreases and the largest HDL increases tended to have the least progression.

Table 1

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<td>Antioxidants</td>
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<td>Intraaortic balloon/assist</td>
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<td>Angiogenesis</td>
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Women who are at higher risk than men for complications from invasive procedures have greatly benefited from statin treatment. In the Cholesterol and Recurrent Events (CARE) trial, women with a myocardial infarction and average cholesterol levels experienced a 40–55% reduction in risk for subsequent coronary events and stroke with the benefit beginning by one year [11]. It is generally agreed that secondary prevention with statin drugs is cost effective in patients with adequate life expectancy.

The cumulative and toxic effects of tobacco on coronary vessel motor tone have been elucidated. Cigarette smoking is the most powerful modifiable risk factor and is the largest single avoidable cause of ill health and premature death in the industrialized world. On a pathophysiologic level, tobacco is a very efficient drug delivery system that impairs endothelial function, probably through lipid peroxidation [12]. Other etiologies and new risk factors have emerged recently. The findings of herpes virus in atheroma, CMV infection in arteries of cardiac allograft recipients, and the serological evidence that Chlamydia pneumoniae infection precedes atherosclerotic lesions that harbor the intracellular pathogen all suggest an etiologic role for chronic infection [12]. Furthermore, up to 40% of people with documented atherosclerosis may have homocysteine abnormalities, and hyperhomocysteinemia may be exaggerated further by smoking, hypertension, and diabetes [13].

Another broad area of investigation involves the angiogenic molecule, vascular endothelial growth factor (VEGF), which is a specific endothelial mitogen released by many cell types in response to hypoxia [14]. The application of this knowledge to the development of collateral circulation and to atherosclerosis is enormous; delivery methods for the protein or the gene are under study.

### 3. Technology Development

The second investigative area involves clinical and applied research. Randomized prospective studies head the list because of their enormous influence on practice. Trials were created to solve important therapeutic dilemmas, generate relevant clinical information and provide conclusions that educate both physician and patient. Their acceptance has been accorded an almost religious sanctification [15]. Unfortunately, in order to eliminate bias as much as possible, randomized studies of coronary artery surgery necessarily enrolled a narrow band of patients with characteristics generally not representative of typical practice. These fastidious designs do not serve coronary artery revascularization well because of inherent heterogeneities in lesion morphology and distribution, patient comorbidities, changing procedures, repeated therapies, and crossovers. Clinical trials often fell short by measuring the operator, not the procedure.

Data interpretation may be slanted by trialists who have become advocates of a particular management or procedure. The answer to individual patient selection is generally not found in clinical trial results, which often contain a multitude of bad results camouflaged by low mortality. The worst of these clinical crimes is perpetrated by the physician who spreads an array of less invasive versus more invasive treatments in front of the patient and then says: ‘it’s your life – go ahead and choose’ [16].

Of the medical/surgical trials, the European Cooperative Study [17] validated the advantage of surgery in multivessel disease with proximal anterior descending stenosis. The Veterans Administration studies were useful for decisions about left main stenosis [19], but generally were marred by less than optimum surgical results. In the Coronary Artery Surgery Study (CASS), survival for medically treated patients was about the same as for those with normal coronary arteries [20]. However, CASS established a large registry more representative of everyday practice, from which more than 150 papers were derived. Virtually every subset of coronary atherosclerosis showed significantly better 5–7 year results of surgery compared with medical treatment [21–27].

Several technological advances over the past three decades have favorably influenced safety and surgical technique. Most notable is the transformation of myocardial protection from normothermia to cardioplegia, conservation of blood and priming solutions, better methods to distribute cardioplegia, progress in graft preparation, modern selective anesthesia with improved monitoring and left ventricular assist devices.

Each of the past three decades has witnessed catheter-based innovations that have revolutionized cardiology. These achievements include significantly less acute arterial closure, fewer emergency bypass operations, lower rates of restenosis, and wider and safer application of interventions for multivessel coronary atherosclerosis. In the 1990s, the evolving pharmacology for heart failure combined with new surgical procedures provide hope for millions of patients.

Even with conventional coronary bypass surgery and more difficult cases, cost per discharge weighted for severity has been reduced as the new era of bypass surgery begins. Shorter length of stay, early extubation, fewer complications, vigorous and early rehabilitation, interaction with social services and a post-discharge follow-up protocol allow many patients to be discharged a few days after surgery. For surgeons, the next wave will be less invasive surgery made more precise by multimedia three-dimensional visualization and robotics. All of the above have a price, but how much is a left ventricle worth and to whom [28]? The only thing that saves us from technology is advanced technology.

### 4. Myocardial Revascularization

After the development of selective cine coronary arteriography and early attempts at revascularization, selection of
surgical candidates became more 'scientific' through arteriographic-based natural history studies. Among the best of these, 10- and 15-year follow-up found that longevity was dependent on the extent of disease and on left ventricular function [29]. These benchmarks stimulated registry development for patients who underwent coronary artery surgery [30,31]. Evidence now exists that coronary artery surgery contributed to the decline in mortality from coronary atherosclerosis [32]. Early risk estimations [33] were modified as surgical populations changed [34,35]. Risk in the 1990s is largely determined by age of the patient, comorbidities, especially renal dysfunction, emergency status, reoperation, and concomitant procedures. The most powerful surgical risk factor is still the surgeon.

Diabetes is now known to be a strong and independent risk factor for atherosclerosis and subsequent events, and diabetes is implicated in wound infection and higher angioplasty restenosis rates. As exercise testing, myocardial scanning and echocardiography have refined patient selection, discoveries about the effects of stunning and hibernation added to our appreciation of myocardial pathophysiology. Stunning is non-uniform and most severe in the subendocardium. Resting myocardial blood flow to hibernating myocardium may well be normal, and repetitive myocardial stunning may account for hibernation [36,37]. Repetitive stunning could be an unrecognized cause of chronic left ventricular dysfunction and even dilated cardiomyopathy.

Vein graft arteriography disclosed the effect of graft hydraulics on proximal lesions [38], factors influencing early closure [39,40], and vein graft atherosclerosis [41,42]. Traditional vein grafting has given way to the new graft of choice, the left internal thoracic artery, more so for grafting the anterior descending coronary artery, initially because of higher patency rates [43] and later because of the advantage in 10- [44] and 15-year [45] survival.

Platelet inhibitors have evolved from aspirin for limitation of vein graft intimal hyperplasia [46] to thrombolytic drugs and now a pure antiplatelet treatment directed against the white clot [47]. For catheter based intervention, the most recent progress has been pharmacology rather than devices. The future for surgical revascularization lies with arterial grafting and less invasive procedures.

5. Selection of surgical candidates

Founded on pathoanatomy, left ventricular status and presence of angina/ischemia, indications for coronary bypass surgery are nonetheless highly individualized. Although patient characteristics may be grouped for statistical analysis, patients come to us at a time and comorbidities vary widely in severity and progressivity. Selection for revascularization has been refined through information gained from natural history, prospective and observational investigation, risk scoring, and experience with continually improving surgical technology. There has been a progressive change in the age of surgical candidates; in 1968 at the Cleveland Clinic, the median age of coronary surgical candidates was 50 years; in 1998, the median age was 66 years. Older age with its attendant infirmities compounds preoperative risk.

Women have a higher risk of mortality from both myocardial infarction and coronary artery surgery. Gender differences have been explained by older age at onset and small stature (body surface area and smaller coronary arteries) [48–50]. Body surface area correlations show that men and women of the same size having similar risk status do not have a significantly different probability of surgical mortality. More recently, additional observers have found that for low and medium risk profiles, women undergoing coronary artery surgery have higher hospital mortality than men [51]. At the higher end of the risk spectrum the mortalities were the same. Nevertheless, revascularization benefits women equally as men [52].

Diabetes, per se, does not affect selection for revascularization procedures; however, atherosclerosis in diabetics is often more diffuse, restenosis rates are higher after angioplasty, and outcome after any form of revascularization is adversely affected. Diabetes and advanced age also affect stroke rates, as does previous stroke, presence of peripheral vascular disease, and hypertension.

Atherosclerosis coexisting in other arterial systems may require staged or simultaneous treatment relative to coronary bypass surgery. Of these systems, internal carotid lesions are most frequent (3–6%) and require the most deliberation [53]. In candidates for coronary bypass surgery, carotid arterial narrowing >70% is generally ignored unless the patient is neurologically symptomatic or an asymptomatic lesion is subtotally (>90–95%) stenotic. For patients who require carotid endarterectomy, the choices include: carotid surgery staged first in patients with stable coronary atherosclerosis; simultaneous carotid and coronary surgery; and coronary surgery first followed by elective carotid endarterectomy.

Poor left ventricular status is far less ominous today compared with the early era of coronary artery surgery. Four factors have expanded the indications for surgery in patients with a left ventricular ejection fraction <0.35: (1) documentation of viable/non-viable myocardium; (2) improved myocardial protection and intra-aortic balloon pumping; (3) internal thoracic artery grafting; (4) left ventricular restorative procedures.

Across this continuum of three decades, we have seen an early era of procrastinating with medical treatment, reluctant acceptance of coronary artery surgery, broader surgical indications, and now, almost unbridled enthusiasm for cardiologic interventions [54]. Treatment tends to outrun methodology because measurable subsets of patients are difficult to categorize, collect, and analyze without bias. Selection for revascularization should endeavor to relieve symptoms, protect the left ventricle, improve survival, and produce a favorable effect by reducing subsequent cardiac events. We are concluding an era marked by a consistent trend toward
6. Saphenous vein graft disease

Vein grafts demonstrate endothelial proliferation as soon as they are connected to the arterial circulation. Any trauma during procurement exaggerates this response and may serve as a nidus for early atherosclerosis. Whereas arterial smooth muscle is adapted to pulsatile flow, smooth muscle in transplanted veins exhibits a proliferative response [56]. Veins are poorly suited to inhibiting the platelet-mediated thrombotic events that characterize arterial circulation.

Saphenous vein graft disease is composed of three pathophysiologically linked processes: thrombosis, intimal hyperplasia, and atherosclerosis [57]. These three factors account for the marked attrition of saphenous vein grafts, especially after the fifth to seventh postoperative year. This phenomenon is graphically depicted in the angiographic investigations conducted by Fitzgibbon and colleagues [58] who compiled serial angiographic results of 5000 saphenous vein grafts in 1388 Canadian military personnel (Fig. 1). Early vein graft patency was 88%; 1 year, 81%; 5 years, 75%; and 10–15 years, 50%. Approximately half of vein grafts showed luminal defects at 5 years and 81% had lumen defects at >15 years. Early and late factors influencing saphenous vein bypass graft patency are summarized in Table 2. Technical factors and poor arterial runoff account for most early graft closure; late failure relates mainly to conduit atherosclerosis. Vein graft thrombosis has been correlated with cigarette smoking [59].

The native artery distribution supplied by the afflicted vein graft is predictive of death and other cardiac events [60]. Late stenosis in an anterior descending vein graft predicts a significantly greater adverse event rate than atherosclerosis in the native coronary circulation or vein graft atherosclerosis in veins used to bypass the right or circumflex regions.

There is now incontrovertible evidence that lipid lowering therapy promotes plaque stabilization by reducing the lipid content of the lesions, which decreases the shear stress at the edge of the fibrous plaque. This stabilization leads to reduction in risk of acute ischemic events and death, for patients with coronary atherosclerosis. The question is how well does therapy affect vein graft atherosclerosis?

The cholesterol lowering atherosclerosis study (CLAS) showed that lipid lowering drugs may reduce progressive vein graft atherosclerosis [61]. More recently the Post Coronary Artery Bypass Graft Trial studied lovastatin alone or combined with cholestyramine and low-dose anticoagulation in patients with vein graft atherosclerosis [62]. When LDL was lowered to 85 mg/dl or less by aggressive treatment, additional revascularization by angioplasty or bypass surgery occurred significantly less frequently compared with moderate treatment (higher LDL) (Table 3). However only about one-third of treated patients reached their goal of LDL 100 mg/dl (2.6 mM/l) or less. Progressive coronary disease at 4 years was documented in 27% of the patients whose LDL levels were lowered aggressively compared with 39% in those who achieved moderate lowering of LDL. Warfarin appeared to have no effect.

Regression of plaque area may occur by one or more of these mechanisms [9]: (1) depletion of cholesterol esters, which may stabilize the plaque and may reduce stenosis by 10–20%; (2) lysis of occlusive thrombi or mural thrombi; (3) wound healing that may favorably remodel an acutely

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**Table 2**

Factors influencing patency of saphenous vein graft used in coronary artery surgery [56]

<table>
<thead>
<tr>
<th>Early vein graft patency</th>
<th>Late vein graft patency</th>
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<tr>
<td>Major determinants</td>
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<tr>
<td>Endothelial injury</td>
<td>Elevated blood lipids</td>
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<tr>
<td>Low flow</td>
<td>Plaque rupture and late thrombosis</td>
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<td>Technical errors</td>
<td>Lack of or inadequate lipid-lowering therapy</td>
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<td>Aspirin</td>
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<td>Major late contributors</td>
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<tr>
<td>Bypass of circumflex or right coronary artery</td>
<td>Cigarette smoking</td>
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<tr>
<td>Non-sequential grafting</td>
<td>Diabetes mellitus</td>
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</tbody>
</table>
Table 3

The post-CABG trial [62]

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<thead>
<tr>
<th></th>
<th>Aggressive treatment</th>
<th>Moderate treatment</th>
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</thead>
<tbody>
<tr>
<td>Disease progression (%)</td>
<td>27</td>
<td>39</td>
</tr>
<tr>
<td>Graft occlusions (%)</td>
<td>10</td>
<td>16</td>
</tr>
<tr>
<td>New lesions (%)</td>
<td>10</td>
<td>21</td>
</tr>
<tr>
<td>Percent stenosis (Δ)</td>
<td>7.9</td>
<td>13.3</td>
</tr>
<tr>
<td>Minimum lumen diameter (Δ)</td>
<td>-0.197</td>
<td>-0.379</td>
</tr>
<tr>
<td>Repeat revascularization (%)</td>
<td>6.5</td>
<td>9.2</td>
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7. Arterial grafting

The single greatest determinant of late outcome is the type of bypass conduit used for grafting. The left internal thoracic artery grafted to the anterior descending is a more important predictor of survival than progressive coronary artery disease [45]. What makes the internal thoracic artery a biologically better graft compared with other conduits? The answer lies somewhere in the structure and function of the artery where the media receives entire blood flow from the lumen [63]. This metabolically active conduit releases endothelium derived nitric oxide and prostacyclin [64]. These favorable biologic properties inhibit mitogenesis and smooth muscle proliferation [65] which serve to protect against thrombosis and inhibit atherosclerosis. The endothelial release of biochemical mediators promotes graft longevity.

As results of internal thoracic artery grafting have been publicized, there has been an upward trend in usage, particularly in older patients, in women, and for emergency revascularization. Lower hospital mortality is also correlated with internal thoracic artery grafting [66,67]. This fact, coupled with higher graft patency and favorable long-term effects on survival and reduction in cardiovascular events, has extended the role of arterial grafting. Internal thoracic artery grafting is now indicated in old or young, with good or bad left ventricular function, single- or multi-vessel disease, diabetes, and even in emergency patients who can be temporarily stabilized.

Relative contraindications to internal thoracic artery grafting include patients with previous chest wall radiation, brachiocephalic arterial lesions, notably proximal subclavian atherosclerosis or in reoperative situations in which replacement of a patent atherosclerotic vein graft by an internal thoracic artery could result in a malperfusion syndrome [68,69]. Hypoperfusion is largely preventable and may result from technical error such as a short pedicle, arterial spasm, small conduit, subclavian steal or stealing from large intercostal side branches, hypotension, myocardial stunning or replacement of high flow by low flow conduit. Free internal thoracic artery grafts used in patients with brachiocephalic stenoses and in reoperations may prevent malperfusion. The main advantage of free grafts is to avoid crossing the midline with an in situ right pedicle and to gain length for more distal anastomoses [70].

Patient gender, diabetes, age, left main disease and poor left ventricular function, should no longer be considered germane to the indications for internal thoracic artery grafting [71]. It appears, however, that many surgeons are influenced by these factors as reflected in internal thoracic artery usage reported from three large registries: internal thoracic artery use in northern New England from 1992 to 1995 ranged from 42 to 95% (mean 82%) [72]; the Veteran’s Administration experience ranged from 39 to 83% (early 1990s) [73]; the New York state cardiac surgery database for 1996 reported 19 659 isolated bypass graft cases, of which 13 875 (71%) had single internal thoracic artery grafting and 1554 (8%) underwent bilateral internal thoracic artery grafting [74]; the Society of Thoracic Surgeons database found a 73% usage of single internal thoracic artery grafts in 1996, of 153 000 cases entered and bilateral internal thoracic artery usage was only 4% [75]. Collectively, this recent data means that only 75% of patients receive internal thoracic artery grafts, and 4–8% receive bilateral internal thoracic artery grafts. Our contention is that these usage rates are too low, considering the advantage of using arterial conduits for anterior descending revascularization in all patient subsets.

The concept of ‘saving’ one internal thoracic artery for use in a reoperation is flawed. The first operation should be designed for the best overall outcome. The survival advantage with internal thoracic artery grafts increases with time as vein grafts close [44] with benefits realized throughout a 15-year follow-up [45]. There is ample evidence that late myocardial infarction and reoperation rates are significantly reduced by the use of one internal thoracic artery graft to the anterior descending. Initial selection of the internal thoracic artery graft is more important prognostically than progression of coronary artery disease. The gain in life expectancy correlates with the amount of left ventricular muscle perfused by internal thoracic artery grafts. The overwhelming conclusion is that the internal thoracic artery graft is the conduit of choice and should not be withheld from any group of patients.

Angina is predicted to recur at a linearized rate of 3–4% per year after the first year. The clinical result generally reflects the anatomic result. The recurrence of angina is attributed to obstructive changes in vein grafts or progressive coronary atherosclerosis. Consistent and prolonged angina relief is generally greater in patients with complete revascularization.

Is return of angina immutable [76]? The risk of return of angina rises continuously after the first 2 years and is influenced by demographic variables, previous angina status, left
ventricular function, distribution of coronary atherosclerosis, and comorbidities such as obesity, diabetes and preoperative lipid levels. Later return of angina is only modestly affected by procedural variables. In registry patients spanning 1971–1992, 61% of patients were angina free at 10 years and 38% at 15 years. Note that this era was marked by less internal thoracic artery usage and less effective lipid lowering therapy.

Late freedom from angina is related to factors in the patient’s individual characteristics, not necessarily the performance of the graft(s). In the first two decades of coronary artery surgery, angina recurrence rates were not different between patients who had received arterial versus all vein grafts. However, vein graft patients with angina have a lower survival than internal thoracic artery graft patients with angina. Therefore, the rate of angina recurrence appears less severe than if more patients had survived, i.e., people with angina and vein grafts only are more likely to die. Preliminary information suggests that bilateral internal thoracic artery grafting may significantly reduce the incidence of angina recurrence after the first myocardial infarction [77].

Given that an in situ left internal thoracic artery grafted to the anterior descending adds longevity and reduces subsequent cardiovascular events, will bilateral internal thoracic artery grafting add even greater value? Until recently, no gain in life expectancy was demonstrable for more than one internal thoracic artery graft. The reasons are that the internal thoracic arteries are used in various combinations, not only to different arteries and their branches, but also as sequential, free (aorto-coronary), natural Y and T grafts. Further, the in situ right internal thoracic artery may have lower patency than the left internal thoracic artery, due in part to right coronary artery branch location, definitely lower patency with free graft placement to the right coronary artery, and potentially lower patency when the transverse sinus route is used for circumflex revascularization.

The third reason is that the left coronary artery branches are prognostically more important than the right coronary artery and its branches. Internal thoracic artery grafts to the anterior descending have significantly higher patency than to other arteries. If internal thoracic artery grafts are used in combination with vein grafts, survival and other events are somewhat dependent on the rate of vein graft atherosclerosis. Finally, 10 years is a minimum follow-up necessary to show advantage of extended internal thoracic artery grafting. Comparative cohorts have, in the past, had few bilateral internal thoracic artery graft patients who have been followed 10 years or longer.

Recently, results from a landmark surgical series documented the efficacy of bilateral internal thoracic artery grafting [78]. Fig. 2 illustrates differences in survival data for single and bilateral internal thoracic artery patients, compiled from 1971 through 1989. The overall hospital mortality was 0.7%. Note that the survival curves begin to separate at the 6th–7th year in favor of bilateral internal thoracic artery grafting. At 5, 10 and 15 years, survival for bilateral internal thoracic artery grafting was 94, 84 and 67%, compared with 92, 79 and 64% (P < 0.001). The insert shows the risks of late death and reoperation for single compared with bilateral internal thoracic artery grafting: all patients, 1.31; for reoperations, 3.74; late death or reoperation, 1.61. Reoperative-free survival and freedom from additional revascularization were significantly higher in the bilateral subset. The risk of late death, reoperation or both is shown for all patients, those <50 years, 50–60 years, and >60 years, over a median follow-up of 10 years (Fig. 3).

Most of these internal thoracic artery grafts were performed as single distal anastomoses. Sequential grafting with side-to-side anastomoses and Y and T grafts were performed in greater numbers after 1989. Twelve percent of the

Fig. 2. Survival curves over 10–12-year follow-up for bilateral internal thoracic artery grafts compared with single internal thoracic artery grafts alone or with vein grafts. The curves show a significant advantage for survival and reoperation free survival in bilateral internal thoracic artery subsets compared with single internal thoracic artery subsets. The insert shows the risk of late death and reoperation comparing single internal thoracic artery grafting with double internal thoracic artery grafting [78].
2001 bilateral internal thoracic artery graft patients had free (aorto-coronary) grafts and 436 (21.8%) of the bilateral group had arterial grafts only. The only morbid event that differed between the bilateral and single internal thoracic artery graft groups was sternal wound complications, 2.5% and 1.4%, respectively.

Bilateral internal thoracic artery usage improved survival over that of single internal thoracic artery grafts in all age groups, except the group 50 years of age or younger. Although the already low death rate in the latter group was not affected, bilateral grafting significantly lowered the probability of reoperation. In fact, bilateral grafting improved reoperation-free survival for all age groups. For patients in the single internal thoracic artery graft category, the risk of reoperation was higher and stratified according to age, with the younger patients having the highest risk of reoperation. While bilateral internal thoracic artery grafts did not materially affect survival in patients with moderate or severe left ventricular impairment, bilateral grafting significantly lowered subsequent reoperation and balloon angioplasty rates for these patients.

In those years (1971–1989), diabetic patients of both genders were far less likely to receive two internal thoracic artery grafts. Subgroup analyses of diabetes versus non-diabetes did not show improved survival for diabetic patients with bilateral internal thoracic artery grafting, but hazard interaction analyses did. The covariates of diabetes with peripheral vascular disease and abnormal left ventricular function cloud the issue. Nevertheless, diabetic patients with bilateral internal thoracic artery grafts had fewer reoperations and subsequent angioplasty. It appears from these and other studies that internal thoracic artery grafting provides similar benefit to diabetic and non-diabetic patients, but does not negate the adverse effects of diabetes on survival [79]. Recent studies confirmed that bilateral internal thoracic artery grafting was a predictor of lower rates of late myocardial infarction, angina recurrence, and composite end points for cardiac events [80,81].

Complications are possible with all of the above conduits, but infection with bilateral internal thoracic artery grafts, more so in diabetics, has negatively influenced bilateral procurement and, as registry data indicates, only 4–8% of recent primary coronary artery surgery cases involved bilateral internal thoracic artery grafting.

Clinical investigations have shown that the incidence of mediastinitis is correlated with diabetes, obesity and number of blood transfusions [82] and, more recently, beta adrenergic drugs have been implicated [83]. What measures can reduce mediastinitis in bilateral internal thoracic artery grafting? Surgical technique is the key to the irreducible minimum. Research has shown that injudicious electrocautery and wide musculo-fascial pedicle dissection devascularize sternal collateral supply and correlate with pulmonary dysfunction, which implicates mechanical strain and sternal instability preceding infection [84].

High blood glucose increases the risk of mediastinitis. Blood sugar values of >200 mg/dl or greater in the first 2 postoperative days are associated with more infection [85]. Glucose management is complicated by the fact that many patients are resistant to insulin after cardiopulmonary bypass. The hyperglycemic state may lead to abnormalities of leukocyte function: abnormalities in granulocyte adherence, impaired phagocytosis, delayed chemotaxis and depressed bacteriocidal capacity. Sternal blood flow in diabetics is not compromised [86].

The above findings may be incorporated into a protocol for all patients, not just patients who undergo bilateral internal thoracic artery grafting: (1) dissect narrow internal thoracic artery pedicles minimizing use of low intensity pinpoint electrocautery, confined to arterial branch division; (2) change gloves after dissection and periodically during long cases. We suggest glove change after sternal wire insertion, and prior to subcutaneous and skin closure [87]; (3) nasal colonization with staphylococcus has been associated with subsequent wound infection and may be eradicated by local application of an antibiotic [88]. DNA fingerprint analysis has shown identical genotypic patterns of S. aureus from the nose and from mediastinal drainage; (4) manage blood sugar assiduously in the perioperative period, keeping blood sugar levels below 200 mg/dl; (5)
perform the skin closure in diabetic patients using vertical mattress sutures of polypropylene, and leave sutures in place for 2–3 weeks. Although this is not yet proven, this is a more secure closure that theoretically prevents contamination from outside; (6) administer a second dose of antibiotics at the conclusion of the operation. We have not been persuaded that figure-of-eight or other methods of suture are superior to heavy single interrupted suture. Wires.

The above protocol coupled with uncomplicated surgery comprises the best measures available to prevent superficial or deep wound infection.

Thus far, bilateral internal thoracic artery grafting as part of all-arterial grafting is the most enduring revascularization strategy. Bilateral internal thoracic artery grafting for left coronary branches is indicated in the vast majority of patients, including those with diabetes. In addition to these durable conduits, outcome is enhanced today by lighter, customized anesthesia, earlier rehabilitation, and effective lipid lowering therapy.

The issues that must be examined with extended usage of arterial conduits involve technical adeptness, complication rates, and long-term performance. Each arterial extension, while potentially better than vein grafting, must be viewed within this perspective. For example, radial artery grafts carry minimal risk to hand circulation, are as facile to use as vein grafts, carry no prospect for added complications, may require intermediate-term pharmacologic management, and have results that are potentially better than vein grafts [89]. This preliminary information has led to an upswing in radial artery graft usage for arteries outside the left anterior descending territory. In one large series of routine use of unilateral and bilateral radial arteries in coronary artery bypass graft surgery, 95.7% patency of radial artery grafts 12 weeks postoperatively was reported [90]. Mid-term results in another experience found 93.1% patency of radial artery grafts at 18 months [91]. Unresolved issues include the best antispasm medication, aorta versus internal thoracic artery for proximal anastomosis, results of sequential radial artery grafting, and whether this conduit should be used for anterior descending grafting [92,93].

The radial artery displays a thicker intima and media compared with the internal thoracic artery. Myocytes are organized in tight layers and nutrition for this media appears to occur from the lumen side [94]. Vasospasm defects were noted in 5% of cases in one series [89] and 10% in another [92]. Currently, diltiazem usage to prevent vasospasm is not standardized and the negative chronotropic effect creates early postoperative problems with blood pressure control that may even prolong intensive care unit stay [95]. Even worse, fewer than half of patients from one large experience continued diltiazem therapy for 1 year [90] presumably because of side effects or change in medication by the cardiologist. The cost of diltiazem prophylaxis is approximately $600/year.

Experiments indicate that diltiazem used empirically to prevent radial artery vasospasm has only a slight effect on human radial artery contractions, whereas organic nitrates are much more effective [96]. While not proven clinically, nitroglycerine may be more effective in reversing a sustained contraction of the radial artery graft and long-term nitrates may be a more reasonable choice for prophylaxis. Adenoviral-mediated gene transfer of bovine endothelial nitric oxide synthase to human radial arteries markedly inhibits radial artery contractions, indicating that gene therapy may be a future method of preventing vasospasm [97].

A permanent revival of the radial artery seems assured. Progress has been made in procurement technique, bathing solutions and systemic pharmacology to minimize spasm.

Gastroepiploic artery (GEA) usage is also supported by excellent patency results. In conjunction with the left internal thoracic artery to the anterior descending graft, intermediate-term results of GEA grafting are outstanding [98]. Nonetheless, procurement in the obese is difficult and the conduit is vulnerable to twisting and technical error. The gastroepiploic artery is also prone to spasm and tends to be smaller at the point of anastomosis than other arteries used for coronary bypass grafting. Its length is not conducive for wide application. Abdominal complications are infrequent, although pancreatitis has been reported. The literature indicates that the best long-term results occur with use of both internal thoracic arteries which can be supplemented by radial and gastroepiploic grafts to provide all arterial grafting for most patients excepting the very elderly. The inferior epigastric artery is also somewhat difficult to procure, shorter, and generally relegated to secondary targets. These arteries are useful when wide revascularization is indicated in the face of absent or unsuitable saphenous veins.

8. Catheter-based interventions

The evolution in cardiology interventions has shifted to pharmacology. Current drugs to diminish restenosis and thrombosis involve new antiplatelet therapy. In prior years treatment has been misdirected toward the red clot by use of heparin and warfarin [47]. Today the approach preferentially targets platelets, i.e. the white clot. Thrombus is actually an admixture of red and white clot, but the white clot component was neglected because no treatment existed. Balloon injury may modulate smooth muscle function from quiescence to a proliferative, migratory and extracellular matrix-producing phenotype [99]. After vessel injury, platelets secrete growth factors that promote cell proliferation leading to restenosis and accelerated atherosclerosis. Platelets promote inflammation in the vessel wall through a protein ligand known as CD-40. Somewhere between 50,000 and 80,000 receptors – IIb/IIIa integrin adhesion molecules – are located on each platelet. The new classes of GPIIb/IIIa drugs inhibit platelet aggregation potently. One drug, abciximab, blocks over 80% of platelet receptors and shows a sustained inhibitory effect.
Several other classes of agents may have salutary effects on restenosis and thrombosis. Antioxidants such as probucol also inhibit production and release of growth factors such as PDGF and cytokines like interleukin-1 [100]. Alpha tocopherol counteracts smooth muscle mitogenesis by restoring nitric oxide release from cells inhibited by oxidized LDL. Antioxidants inhibit macrophage binding, increase resistance of endothelial cells and macrophages to oxidized LDL, and decrease platelet activation. The next wave of therapy will be oral agents for platelet inhibition and prevention of plaque fissure formation.

The cumulative effect of new pharmacology has been to decrease arterial closure and restenosis, which has significantly diminished the incidence of emergency surgery. The EPISTENT trial which enrolled a variety of patients with stent placement found that Ilb-IIIa blockade improved mortality and myocardial infarction [101] and reduced emergency operation by half. Also, the incidence of restenosis in diabetics was reduced by half. There was no untoward bleeding associated with their use. Platelet Ilb/IIa inhibitors are now administered for unstable angina with the intent to stabilize the patient and reduce events prior to diagnostic catheterization. Since complications are reduced, the indications for multivessel angioplasty and stenting have been expanded.

The overall effects of these new drugs on angioplasty results are not yet known. The new pharmacology was not available for routine use in angioplasty/surgery trials. What is known from comparative studies of angioplasty and coronary artery surgery is that for non-diabetic patients, multivessel balloon angioplasty achieves 3–5 year survival similar to that of coronary artery surgery [102]. Analysis of the secondary endpoints discloses that functional status, amount of medication and exercise tolerance (exercise induced ischemia), and silent ischemia were improved by or occurred less often after coronary artery surgery than after angioplasty. In fact, in virtually all multivessel angioplasty/surgery trials, coronary artery surgery patients were less likely to have angina at all levels of severity, and there were lower rates of exercise induced ST changes in 3–5 years of follow-up.

Several facts are notable in these comparisons. (1) Apart from symptoms, other aspects of quality of life were equivalent with either method of revascularization. (2) Thirty percent of angioplasty patients in the Bypass Angioplasty Revascularization Investigation (BARI) trial underwent coronary artery surgery within the first 5 years of follow-up [103]. (3) Diabetes is recognized as an independent risk factor for angioplasty – a risk that markedly diminishes survival (80.6% for surgery vs. 65.5% for angioplasty survival at 5 years in BARI) [104]. Diabetes is a strong and independent risk factor for atherosclerosis, especially in women and imposes a greater risk of death, myocardial infarction and stroke. The combination of diabetes and an artery that has been instrumented appear to be additive variables that increase the risk of progressive narrowing which explains the high adverse event rate observed in diabetic patients [105]. While restenosis in diabetes did not reach statistical significance over non-diabetes, new coronary artery lesions occurred more frequently and were more unstable in the diabetic patient. Diabetic patients have shown greater rates of repeat revascularization, cardiac events, and death after angioplasty, which has also been attributed to greater frequency of incomplete revascularization [106,107]. (4) In these trials, use of internal thoracic artery grafts to the anterior descending was inconsistent [108], ranging from 37% in the German Angioplasty versus Bypass Surgery Investigation (GABI) to 82% for BARI. Since trial patients were selected on the basis of indications for angioplasty, they tended to be younger than the average surgery patient and have more focal disease, most often with good arterial runoff and open, not occluded, vessels. Few patients had all-arterial grafting. (5) Cost rose with the number of vessels dilated and reached 95% of coronary artery surgery costs in triple-vessel disease by 5 years [109]. Perhaps, future catheter-based interventions and new pharmacology will be associated with fewer episodes of repeat revascularization including referral to surgery. New drugs are expensive (e.g. $1400 for abciximab, the human-murine chimeric monoclonal antibody) and stenting approximately $1000 more expensive than angioplasty.

Although stents are technically less time consuming than angioplasty, enthusiasm for primary use of stents may be waning. High cost (stents are one-half the price in Europe compared with the United States), stenosis rates similar to those of angioplasty [110], the problem of aggressive in-stent restenosis, which is resistant to treatment (restenosis rates 50–80%), and high event rates after stenting for late saphenous vein graft disease counterbalance the ease of stent implantation. In a review of published studies on coronary stents over a mean follow-up of 32 months, the death rate was 5%, early myocardial infarction rate 5%, early restenosis 20%, late restenosis 3%, referral to coronary artery surgery 8%, and any cardiovascular event 29% [111].

The need for coronary artery surgery after successful angioplasty has not been reduced and correlates with the number of critical lesions dilated and their location [112]. If complete revascularization cannot be achieved by angioplasty, coronary artery surgery should be considered, especially if all-arterial grafting can be safely undertaken. Any revascularization of the anterior descending, whether it is catheter-based or by less invasive surgery, must be measured long-term against the left internal thoracic artery graft to the anterior descending. In our observational study comparing internal thoracic artery grafting with saphenous vein grafting for anterior descending revascularization, 80% of the patients who received internal thoracic artery grafts were alive 20 years later, and 60% survived event-free [113]. Evidence of non-critical lesions in the circumflex or right coronary artery vessels at the time of grafting adversely affected the 20-year event-free results. However,
those differences were significantly less in patients receiving a left internal thoracic artery graft to the anterior descending coronary artery compared with vein graft patients. Most reinterventions occurred after the tenth year of follow-up.

A more recent and larger experience of internal thoracic artery grafting for single-vessel anterior descending stenosis reviewed 2,072 consecutive patients [114] treated by conventional median sternotomy and cardiopulmonary bypass, from January 1, 1971 through December, 1996. The mean follow-up was 12 years and the longest, 26 years. Hospital mortality was 0.2%, with no deaths in the past 17 years. The 20-year actuarial survival was 72%. Fig. 4A shows that the study group outperformed age and gender matched survival of the US population. The presence of disease in other coronary arteries affected late survival. At 20 years, 60% were free of either angioplasty or coronary reoperation. (Fig. 4B)

In 1996, the mean length of hospitalization was 5 days, and there were no instances of return to surgery for bleeding in the most recent experience.

9. Reoperation

The incidence of reoperation increases with lengthening postoperative interval rising to a high of 30% at 15 years [115]. In recent experience, the rate of reoperation has been reduced by catheter interventions and increasing use of longer-lasting arterial conduit. Nationwide, the incidence of reoperations in isolated coronary artery surgery practice varies between 7% and 9% (Society of Thoracic Surgeons database). Our reoperation rates for isolated bypass grafting are depicted in Fig. 5. The down slope in the 1990s probably reflects the peak of balloon angioplasty and stenting of atherosclerotic vein grafts. The rate of reoperation has not increased because of angioplasty, stents, lipid lowering drugs, use of the left internal thoracic artery for anterior descending grafting and a progressively older population facing their first coronary bypass operation.

Compared with balloon angioplasty, stenting for treatment of patients with diseased saphenous vein grafts has resulted in significantly better event-free survival (73% vs. 58%) at 8 months follow-up, but the known restenosis rate of 37% was no better statistically than the restenosis rate of 47% for balloon angioplasty [116]. Other reports indicate that less than a third of the patients with previous bypass surgery who subsequently had angioplasty of the vein graft remained event-free after 5 years [117]. The long-term results are better in angioplasty patients who require graft dilatation within the first operative year. There appear to be higher death and event rates after vein graft stenting compared with native coronary stenting. The reality is that vein graft atherosclerosis is a bad problem, not easily treated by catheter-based interventions or surgery.

Overall, the single greatest determinant of need for repeat revascularization is the type of conduit used at the first procedure [118]. Performance of an internal thoracic artery graft to the anterior descending significantly reduces the reoperation rate by a factor of two [44] and now abundant evidence exists that two internal thoracic artery grafts offer even greater reoperation-free survival [78].

The clinical and angiographic characteristics of patients referred for cardiology or surgical treatment of vein graft disease are vastly different. Patients having reoperation tend to be male with a higher incidence of diabetes and other comorbidities and larger regions of myocardium in jeopardy. The angioplasty-referred patient is more likely to have a patent arterial graft to the anterior descending coronary artery or multiple functioning bypass grafts, and thus is more protected going into angioplasty [119].

Reoperations are generally performed for vein graft atherosclerosis, progressive atherosclerosis in ungrafted arteries, or both. Balloon angioplasty is often reserved for new plaques in ungrafted native vessels, lesions distal to a patent anastomosis, early anastomotic stenosis or isolated focal vein graft atherosclerosis in patients protected by patent grafts to other coronary arterial systems.

Anterior descending vein graft atherosclerosis carries a worse prognosis than vein graft atherosclerosis to the right coronary artery or circumflex systems, and a worse prognosis than anterior descending atherosclerosis per se [60].

The reason is that apart from the left main trunk, the anterior

Fig. 4. (A) Twenty-year event-free survival after left internal thoracic artery grafting for single vessel anterior descending disease compared with age and gender matched US population [114]. (B) Twenty-year hazard function curves show that 60% of patients who received an internal thoracic artery graft for isolated anterior descending disease survived free of angioplasty and/or coronary reoperation.
descending affects longevity and cardiovascular events more than any other coronary vessel [120]. Vein graft atherosclerosis exhibits a diffuse concentric pattern with a weak fibrous cap that exposes the cellular elements of lipid debris to the blood stream. Inflammatory cells infiltrate the plaque more than in native vessel atherosclerosis, and the lesion is more friable and fragile, and prone to embolism. Therefore, surgery is probably a better long-term option than stents or balloon angioplasty for late anterior descending vein graft disease. Patients with vein graft atherosclerosis in the anterior descending distribution benefit from reoperation with significantly higher survival compared with medical treatment [115].

Ideally, a diseased vein graft should be replaced by an internal thoracic artery. Survival trends after reoperation indicate better results with internal thoracic artery grafting compared with vein graft replacement [115]. However, potential for malperfusion exists in reperfusion of large territories served by a high flow diseased vein graft. If late patency of the radial artery conduit proves to be consistently high, it could become the leading conduit replacement for a saphenous vein graft to the anterior descending coronary artery.

The question is still debated whether to replace grossly non-diseased vein grafts at the time of reoperation for atherosclerosis in adjacent coronary systems. Some advocate leaving the vein graft alone, citing a higher 1–3 year survival than with replacement [122]. To apply this approach uniformly is not acceptable for several reasons. It depends on the patient’s age; in the very elderly non-replacement may lower risk, but deterioration of these conduits is inevitable and virtually all 20-year-old grafts (the 16–20% that are open) are atheromatous and calcified. De novo atheroembolism from older vein grafts remains a possibility [123]. For younger patients conversion to arterial grafts is a better strategy. Other characteristics are highly individualistic and depend on operative risk, availability of conduits, and concomitant procedures. Shortage of available bypass conduits is less a problem today with greater use of both internal thoracic arteries (available also as free grafts), radial arteries, the gastroepiploic artery, the inferior epigastric artery and both lesser saphenous vein systems.

Reoperative surgery has advanced through technical innovation and experience, not by selection of easier surgical candidates. Prevention of catastrophic hemorrhage [124], improved dissection techniques [125], use of antegrade and retrograde cardioplegia [126], and application of arterial grafting have made reoperation safer. The use of an internal thoracic artery during the first coronary artery operation does not increase the risk of reoperation, and use of an internal thoracic artery at reoperation does not increase the reoperative hospital mortality or morbidity [127].

A third or fourth coronary artery operation obviously requires careful selection. We have found that patients >70 years old have increased risk at reoperation, and length of stay outlier costs are disproportionately higher compared with primary coronary artery surgery [128]. Yet, the overall five-year survival for those patients discharged alive was 84% after a third coronary operation.

10. Less invasive coronary artery surgery

At the outset of less invasive coronary artery surgery, we have passed through early stages aptly described by Collins as ‘converting an operation that should be totally safe into a hair-raising adventure’ (pers. commun.). Currently a number of incisions have been advocated for less invasive access, including mini-sternotomies, thoracotomies, and thoracic port access with femoral vessel perfusion. (Fig. 6) The ones that spread or remove cartilage, however, have not decreased postoperative pain. Special retractors and heart stabilizing devices for coronary grafting on the beating heart without use of cardiopulmonary bypass have been devised. Drugs that decrease the heart rate have not been effective. Each approach has its proponents – some showing good results with or without cardiopulmonary perfusion, generally with fewer grafts per patient than for traditional coronary artery surgery, no significant reduction in morbidity and a modest, at best, decrease in length of stay.

We cannot invent indications to justify technique. Minimally invasive surgery is misused when it is performed for cosmetic reasons or for marketing purposes, especially when the surgeon does not have the proper background or training. The danger with enthusiasm for evolving techniques is that we can be drawn into a randomized prospective study comparing suboptimal less invasive surgery with catheter-based interventions. The urge to do so should be tempered by the remembrance of the Veteran’s Administration Surgery-Medicine Prospective Trial [129] debate over which briefly retarded development of coronary artery surgery. The goal is to achieve complete revascularization with less pain and shorter length of stay without compromising safe and sound techniques. Internal thoracic arteries must be fully mobilized; techniques must be developed to cannulate intrathoracically; aortic occlusion must be accomplished.

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Fig. 5. Isolated coronary artery reoperations from 1985 through 1997 as a percentage of all isolated coronary bypass operations (Cleveland Clinic Foundation Cardiovascular Information Registry).
Coronary artery surgery is successful today because of excellent myocardial protection, good exposure and clear vision in a dry, motionless field. Ultimately these criteria must be obtained through 1 cm ports aided by cardiac decompression, computer-guided three-dimensional vision and instrumentation and the safest methods of myocardial protection. This technical constellation must be packaged to result in a reasonable operating time and comparable cost. Additional equipment cost may be offset by reduction in personnel cost. For grafting of a single internal thoracic artery to the anterior descending artery, patency must equal the 95% recorded for conventional techniques and achieve 10-year survival in the 90th percentile.

To accomplish direct coronary artery surgery and achieve complete revascularization for multivessel coronary atherosclerosis consistently and, preferably, with all-arterial bypass grafts, cardiopulmonary bypass does appear necessary. Otherwise, we are returning to technical acrobatics, which is not suitable for most surgeons, cardiac operations or patients.

New technology is incredibly innovative. Visual endoscopies have been replaced by image acquisition through video cameras. The ergonomically stressful conventional video monitor displays a two-dimensional reversed image that requires the surgeon to use counterintuitive movements without true depth perception. A flexible camera combined with lightweight head mounted LCD display is one method to provide three-dimensional image [130]. On line monitoring and diagnostic data may be displayed on the head-set viewing screen. Flat panel displays promise even greater clarity.

Another approach is to use CRT optics to provide three-dimensional wide-field vision at a workstation. This viewing technology has been combined with robotics that place a mechanical wrist inside the patient. A computer is inserted between the power and the instrument tip. The surgeon uses instruments (manipulators) attached to a computer that controls the robot, which replicates the movements of the surgeon [131]. The surgeon sits comfortably at a viewing and control console. (Fig. 7) Movement of the detachable instruments, VCR, lights and camera, are voice actuated. The manipulators operate similar to Castro Viejo needle holders to direct the intrathoracic instruments. Large movements outside are scaled down for micromovements and elimination of tremor at the operating site. Tactile sensation will be built in so that the surgeon feels resistance while dissecting or suturing. Thus, robotics coupled with high resolution three-dimensional viewing will provide greater precision, ease of use, and safety. As one manufacturer aptly describes it... ‘surgical technique beyond the limits of the human hand.’ (Intuitive Surgical, Mountain View, CA, pers. commun.).
For surgeons who advocate the beating heart method of perfusion, motion cancellation is another application for surgical robotics. The system tracks motion of the human heart so that all instrument actuators and the camera move along with the heart to make the beating heart appear immobile during construction of the anastomoses.

While evolutionary, all this technology exists today in some form. For port access surgery, robotic activation is the complementary technology that will enable standardization of minimally invasive coronary artery surgery. The aorta must be cannulated by a safe, reproducible technique. Smaller venous cannulae inserted intrathoracically or percutaneously through the jugular vein with vacuum assisted drainage are already available. The jugular route may be used for TEE guided coronary sinus cannulation. The goal of all less invasive surgery should be to stay out of the leg for perfusion and vein procurement.

This software will be interconnected with diagnostic information, intraoperative monitoring, anesthesia and perfusion data, cost accounting and surgical note transcription. The patient will leave the operating room with a complete package of information that is incorporated into the electronic chart (Computer Motion, Goleta, CA, pers. commun.). The impact of an operating room network with augmented dexterity and instrument positioning, integrated data and a complete record is reflected in this utilization/value equation (Fig. 8). The new technology, robotics and methodologies to integrate data will be safe and reliable. There is great potential for ease of use and application to all forms of heart surgery. As operating time decreases, productivity will rise. This new technology has the capacity to cross specialty disciplines and achieve better outcomes at lower cost. As patients are returned to normal activity earlier, the operating room of the future will have great impact socio-economically.

11. Concluding remarks

The future of coronary artery surgery depends on the durability of the bypass graft and the proclivity of serum lipid modification to reduce progressive atherosclerosis. Now at the end of this beginning era, coronary artery surgery enters a new generation that will change our practice and the outcomes of our patients. Surgery will be affected by some predictable cross-currents. Pharmacology and radiation have potential to reduce restenosis following endoluminal, non-surgical approaches. As the human genome is decoded, new drugs will supersede the current statin class to more effectively improve lipid profiles, stabilize plaques vulnerable to rupture and consistently retard progression of atherosclerosis. Identification and treatment of newer atherogenic factors such as homocysteine and inflammatory conditions may further decrease the predisposition to cardiovascular events.

Less invasive coronary artery surgery will become minimally invasive surgery as instrumentation, three-dimensional optics and surgical robot control are integrated into the operating room of the future. Assuming that radial artery patency rates are sustained, the radial and gastroepiploic arteries combined with both internal thoracic arteries will replace vein grafts as the principal conduits for bypass surgery. Angiogenesis may hold promise for patients with diffuse atherosclerosis and viable myocardium.

Most new technology will be applied to minimally invasive surgery for multivessel bypass grafting and concomitant cardiac procedures. When cannulation and myocardial protection is standardized through port access, robotics will add safety and precision to procedures that have developed favorably over the past 30 years. The investment return from new technology will be realized through the operating room of the future. This redesign will finally coordinate diagnostic and procedural data, intraoperative mechanics, a written record, cost accounting and documented visual performance.

The conclusion of this decade marks the end of the beginning, not the beginning of the end. The demise of coronary artery surgery has been predicted with each cardiology advance. Instead, these specialties are even more complementary than before. The fact of the matter is that there is no technical field ahead of thoracic and cardiovascular surgery. The new generation of cardiothoracic surgeons will participate in an array of technology and clinical research unmatched in previous decades. The rate of discovery in science, technology, and clinical revascularization will increase, propelling advances that will make this great surgical enterprise more intellectually stimulating and satisfying.

Of vital importance is the patient who should receive greater benefits and our total devotion [132].

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