Multisection CT Evaluation of the Reoperative Cardiac Surgery Patient

Robert C. Gilkeson, MD • Alan H. Markowitz, MD • Leslie Ciancibello, RT

Development of electrocardiographically (ECG) gated multisection computed tomography (CT) has had a significant, immediate impact in cardiovascular imaging. The capabilities of this new technique have become particularly important in the preoperative assessment of the cardiac surgery patient. Cardiac surgery in the 21st century has become increasingly complex because of an aging population needing multiple procedures. As patients live longer, reoperative surgery is often needed, requiring further complicated intervention. Recent research in cardiac surgery patients has linked atherosclerotic disease of the aorta to the risk of perioperative stroke. Multisection CT has been effective in evaluations of the atherosclerotic aorta, minimizing perioperative stroke risk in these often elderly patients. By using the capabilities of ECG gating, improved CT imaging of the aortic valve has helped guide the surgeon in decisions of aortic valve replacement. Injury to preexisting coronary artery grafts is associated with significant perioperative morbidity and mortality. The superior imaging features of ECG-gated CT have enabled preoperative identification of coronary grafts, preventing injury to these important structures during reoperative surgery. Assessment of normal anatomic structures is also important in preoperative planning. Proximity of the aorta, pulmonary artery, and native coronary arteries to the sternum is an important potential cause of morbidity and mortality, and it can be preoperatively assessed with multisection CT. The advancement of ECG gating has enabled accurate assessment of the coronary arteries, which is particularly important in the preoperative identification of congenital and acquired abnormalities. With continued advances, ECG-gated multisection CT will play an increasingly important role in the evaluation of patients with cardiovascular disease.
Introduction
Cardiac surgery in the 21st century has become increasingly complicated for a number of reasons: (a) patients are living longer and have a number of associated medical comorbidities; (b) reoperations have increased in frequency (1) and are far more complicated than the initial procedure; (c) medical therapy is significantly more effective, and patients who eventually become surgical candidates have more advanced cardiac disease; and (d) multiple cardiac procedures (valve surgery plus revascularization, multiple valve replacements, arrhythmia ablations, complicated aneurysm resections) have become standard procedures. This increasingly complicated patient population requires careful preoperative assessment to minimize the risks of cardiac surgery. Sophisticated evaluations of the thoracic aorta, coronary artery grafts, and the anatomic relationships of normal cardiac structures are needed in the preoperative evaluation of the “reoperative” cardiac surgery patient (ie, one who has previously undergone cardiac surgery). With the introduction of electrocardiographically (ECG) gated multissection computed tomography (CT), we have seen substantial improvements in imaging of cardiovascular disease. These advances have enabled multissection CT to become an important part of the assessment of these patients with complicated cardiovascular disease. In this article, we summarize our experience with multissection CT in the preoperative assessment of the complicated cardiac surgery patient. We describe our imaging technique in these cases and discuss its use in the preoperative evaluation of the ascending aorta, the aortic valve, and coronary artery grafts.

Imaging Techniques
In assessment of cardiac and coronary graft anatomy, all patients are evaluated with multissection CT at our institution with the Philips MX8000 four-section scanner and the Philips IDT 16-section CT scanner (Best, Netherlands). In assessing reoperative cardiac surgery patients with left internal mammary artery (LIMA) or right internal mammary artery (RIMA) grafts, CT scanning from the thoracic inlet to the apex of the heart is performed. Because of the need for extended coverage and the ability to minimize cardiac and coronary graft motion, retrospective ECG gating is performed with a 2.5-mm section thickness and 1-mm reconstruction. To optimize graft visualization, an automated bolus tracking technique is used with a region of interest placed within the ascending aorta. A total of 100–150 mL of contrast material at a concentration of 300–320 mg of iodine per milliliter is used. When a more directed examination of saphenous vein or other coronary grafts is needed and the extent of anatomic coverage is limited, a section thickness of 1 mm and reconstruction interval of 1 mm are used. The 16-section scanner has enabled improved anatomic coverage, shorter breath holds, and smaller volumes of contrast material. Spatial resolution of the 16-section scanner is also superior to that of the four-section scanner. Because of the superior imaging capabilities of the 16-section scanner, all ECG-gated studies are performed with 0.8-mm section thickness and a pitch of 0.24. Dedicated cardiac studies are performed in approximately 18–20 seconds, whereas full graft assessments are 20–25 seconds in duration.

In the population of patients with renal failure who cannot receive iodinated contrast material but do need assessment of aortic atherosclerosis, non–ECG-gated, 2.5-mm images of the thoracic aorta are obtained to assess position and extent of aortic calcification. All studies are reviewed on the Philips MX View workstation with our referring surgeons. Multiplanar (MPR), maximum-intensity projection (MIP), and volumetric reformatations are performed as clinically indicated.
Preoperative Assessment of the Ascending Aorta

The risk of perioperative stroke in patients undergoing cardiopulmonary bypass is well defined in the cardiac surgery literature (2). These patients experience greater morbidity, with significantly longer lengths of stay in intensive care units and rehabilitation facilities (3). A number of authors have defined the significant relationship between ascending and aortic arch atherosclerosis and adverse cardiovascular events during cardiac surgery (4). In a recent study, Morino et al (5) assessed the incidence of cerebral complications in patients undergoing coronary artery bypass grafting (CABG). Multivariate analysis demonstrated that aortic calcification was the only important determinant of perioperative stroke; there was also less risk with complete cross clamping than partial clamping (5). In their population, the risk of neurologic events was 8.7%, whereas in patients undergoing aortic “no touch” surgery there were no cerebral complications. Van der Linden et al (6) studied 921 patients with transesophageal echocardiography before cardiac surgery, with markedly similar results. In patients with atherosclerotic disease of the aorta, the risk of cerebral events was 8.7% versus 1.8% in the absence of aortic disease (6). For some surgeons, this increased stroke risk has been a significant factor in the development of off-pump coronary artery bypass, with documented decreased stroke risk in these patients (7). A number of reports have described the safety of axillary artery cannulation with antegrade cerebral perfusion (8,9) as a low-risk alternative to direct aortic cannulation in patients with significant atherosclerotic disease and increased stroke risk.

Our surgeons routinely perform preoperative assessment of the aorta in the older cardiac surgery patient. When the ascending aorta is free of significant atherosclerotic disease, direct aortic cannulation can be performed safely. Preoperative CT has played an important role in presurgical assessment of this population and resulted in substantial decrease in the prevalence of perioperative stroke in our elderly patients.

Figure 1. Preoperative assessment before aortic valve replacement in a 55-year-old man with a history of congenital bicuspid aortic valve and aortic stenosis. Coronal volume-rendered image shows a small amount of calcium at the level of the aortic valve (lower arrow). The ascending aorta is free of atherosclerotic disease (upper arrow). Direct aortic cannulation can be performed safely.
Preoperative Evaluation of the Aortic Valve

The use of multisection CT with ECG gating has markedly improved the evaluation of the aortic valve (10,11). Once limited by a number of imaging artifacts (12), the CT assessment of the aortic valve and aortic anulus for valve morphology, calcification, and the relationship of the coronary ostia to the aortic sinuses can be easily accomplished (Figs 3, 4). This information substantially affects the type of aortic valve surgery performed. At our institution, the imaging capabilities of ECG-gated multisection CT have played an important role in the preoperative choice of surgical approach and valve bioprosthesis (13).

Figure 2. Imaging evaluation before reoperative CABG in an 83-year-old woman with a history of severe peripheral vascular disease and prior CABG. (a) Axial CT image shows dense calcification in the aortic arch and origin of the great vessels (arrow). The calcium is similar in attenuation to the contrast material within the superior vena cava (arrowhead). (b) Sagittal MIP image shows extensive calcium in the ascending aorta (curved arrow) and arch vessels (straight arrow). (c) Virtual endoscopic image of the ascending aorta shows extensive calcified plaque within the vessel (arrows). Because of the extensive degree of ascending aortic atherosclerotic disease in this patient, axillary cannulation for cardiopulmonary bypass was performed. The patient suffered no neurologic sequelae.
Figure 3. Preoperative assessment of aortic aneurysm in a 63-year-old man. (a) Oblique axial MPR view shows delineation of the patient’s tricuspid aortic valve, with clear definition of the three aortic sinuses and normal-appearing valve leaflets (arrow). (b) Virtual endoscopic image of the valve shows a normal-appearing tricuspid aortic valve.

Figure 4. Preoperative assessment of the thoracic aorta in a 57-year-old man with a history of aortic stenosis. (a) Oblique axial MPR view of the aortic valve shows a bicuspid aortic valve (arrow), with mild thickening of the aortic leaflets and calcification within the aortic sinuses. (b) Virtual endoscopic image of the thoracic aorta shows the bicuspid aortic valve (arrow) and valvular calcification. Note the origin of the left coronary artery within the sinus of Valsalva (L), whereas the origin of the right coronary artery (R) is above the sinotubular junction. Because the ostia of the coronary arteries are less than 180° apart, a stentless aortic valve can be safely placed within the aortic valve position.
Coronary Artery Graft Assessment

There is extensive literature on the assessment of coronary artery grafts with multidetector and electron beam CT. In one study, Ha et al (14) used electron beam CT to assess graft patency and found it had 92% sensitivity for detecting patency of LIMA grafts and 100% sensitivity for detecting patency of saphenous vein grafts. Engelmann et al (15) found that electron beam CT had lower sensitivity for detecting patency of LIMA grafts, but 100% sensitivity for detecting patency of saphenous vein grafts. Although assessment of patency is important in presurgical planning, defining the anatomy of these grafts is critical, and there is a growing literature on using ECG-gated CT for this purpose (16,17).

The development of the LIMA graft marked a significant advance in the field of cardiac surgery. The LIMA graft has shown markedly improved long-term patency rates compared with those of saphenous vein grafts (18) (Fig 5). Although revascularization with the LIMA graft has represented a significant advance in patient care, the majority of patients who have previously undergone LIMA grafting are “graft dependent,” and LIMA injury at reoperation can be devastating. The importance of LIMA graft preservation has resulted in an extensive body of literature on protection of LIMA grafts during reoperative surgery (19–21). In the largest series of patients undergoing reoperative cardiac surgery, injury to the LIMA graft occurred in 5.3% of patients, with a perioperative infarction rate of 50% (22). These authors used chest radiography and cardiac catheterization to identify LIMA grafts that were close to or adherent to the sternum. Unfortunately, these imaging techniques provide insufficient information for avoiding injury to these important grafts upon sternal reentry. We have used multi-section CT to map completely the position of the

Figure 5. Postoperative evaluation of LIMA graft patency in a 73-year-old man. (a) Coronal volume-rendered image of the thoracic aorta shows normal appearance of the LIMA graft (arrow). A = aorta, RVOT = right ventricular outflow tract. Note the normal appearance of the right coronary artery (arrowhead). (b) Sagittal image shows the relationship of the LIMA graft (arrow) to the sternum. Note the distance between the graft and the sternum. This LIMA graft is at low risk for injury during sternal reentry.
Although axial sections provide important information, volume-rendered images have proved to be particularly valuable to the referring surgeon. Our findings during these studies have changed the surgical approach in a substantial number of patients (Fig 7). With the increased frequency of reoperative surgery, coupled with the trend toward minimally invasive cardiac surgery, assessment of the native LIMA is more frequently requested (23). Although extremely rare, postoperative fistulas of the left internal mammary

**Figure 6.** Preoperative assessment for aortic valve replacement in a 72-year-old man who had undergone CABG. Sequential coronal volume-rendered images show relationship of the sternum to the LIMA (arrow) and saphenous vein (arrowhead in b) grafts. The position of the LIMA graft lateral to the sternum makes sternal reentry uncomplicated.

**Figure 7.** Preoperative assessment for aortic valve replacement in a 67-year-old man who had undergone CABG. Axial CT image (a) and sagittal volume-rendered image (b) show adherence of the LIMA graft (arrow) to the inner table of the sternum. Given these findings, the surgeon did not attempt the usual operative dissection of the LIMA graft during the surgical procedure.
artery and vein can occur and must be identified before any attempts at sternal reentry are made (24) (Fig 8).

The improved long-term survival in patients undergoing LIMA grafting has resulted in the increasing use of the RIMA graft for coronary revascularization. Although these patients exhibit low operative mortality and excellent long-term patency rates (25), RIMA grafting is technically more demanding than the LIMA graft surgery. In revascularization of the left coronary system, the RIMA must cross the midline to reach the left

Figure 8. Preoperative assessment for mitral valve replacement and CABG in a 43-year-old woman who had undergone placement of an automatic implantable cardioverter/defibrillator. Physical examination revealed a continuous murmur over the left side of the chest. (a) Axial CT scan shows enlargement of the left internal mammary artery and vein. Note enhancement of both dilated internal mammary artery and vein (arrow). (b) Coronal MIP image shows the dilated, fistulous internal mammary artery and vein (arrow).

Figure 9. Preoperative assessment of the existing RIMA graft in a 67-year-old man scheduled for CABG surgery. (a) Axial image shows the portion of the RIMA graft as it crosses near the sternum (arrow). (b) Curved axial MPR image shows the full course of the RIMA graft (arrow) as it crosses the midline to pass directly behind the sternum (S) and anastomose to the circumflex artery (arrowhead). A = transverse aortic arch.
coronary artery distribution. This pathway often positions the RIMA graft in close apposition to the inner table of the sternum and makes the potential for graft injury during sternal reentry especially high. Several authors have described efforts to protect the RIMA graft from injury at reoperation, including the use of stents in arterial grafts (26). These patients are successfully imaged with multisection CT, which accurately depicts the relationship of the RIMA graft to the sternum in these reoperative candidates (Fig 9).

Although the internal mammary grafts are at particular risk in reoperative cardiac surgery, accurate evaluation of saphenous vein grafts can be equally important. There is a large body of literature about imaging these grafts to assess patency (27); however, little has been written on the preoperative imaging evaluation of their anatomy in the reoperative cardiac patient. Unless the right ventricle is enlarged, saphenous vein grafts are generally farther away from the sternum and are therefore protected during sternal reentry (Fig 10). In the setting of dense adhesions and obliteration of normal anatomic landmarks, damage to patent

Figure 10. Postoperative evaluation of graft patency in a 67-year-old man. (a) Coronal volume-rendered image shows normal postoperative position of the right (R) sided and left (L) sided saphenous vein grafts. (b) Axial volume-rendered image in a cephalocaudal orientation shows relationship of the left-sided saphenous vein (long arrow) to the sternum (short arrow). (c) Sagittal volume-rendered image shows position of the right-sided saphenous vein graft (arrow) to the sternum.
Saphenous vein grafts can occur at any time when their presence is not anticipated (Fig 11). Saphenous vein grafts are more prone to early atherosclerotic disease (28), and manipulation of a patent but diseased graft (Fig 12) can shower emboli into the distal circulation, creating irreparable myocardial damage. Because the saphenous vein graft is anastomosed to the anterior aspect of the ascending aorta, aneurysmal change in the aorta may displace the attached graft toward the...
sternum, increasing the risk of injury during sternal reentry in reoperative cardiac surgery (Fig 13). In other cases in which aortic aneurysm surgery is planned, identification of the relationship of the saphenous vein graft to the aneurysm can be important to the referring surgeon (Fig 14.) In patients with a history of multiple coronary revascularizations, the use of a lateral thoracotomy and the descending aorta provides a technically difficult but safe approach for coronary revascularization with saphenous vein grafts. The noninvasive use of ECG-gated multisection CT allows successful evaluation of these grafts and in some patients obviates preoperative cardiac catheterization (Fig 15).
Postoperative aneurysms of the aorta and coronary artery grafts have been well characterized in the radiology literature (29). Pseudoaneurysms of the aorta can occur at a number of sites, including the aortic cannulation site, bypass graft anastomoses, and needle venting sites (30). Aneurysms of coronary artery grafts are a rare but well-recognized entity in cardiac surgery patients. Over 50 cases of aneurysms and pseudoaneurysms of saphenous vein grafts have been reported in the literature since 1975. True aneurysms will occur as late postoperative complications, often manifesting 5 or more years after the initial surgery. Pseudoaneurysms may develop early in the clinical course, often at the anastomotic site. Patients may be asymptomatic, but they can present with chest pain, superior vena cava obstruction, or hemothorax. Fistulas to the right atrium and ventricle have been reported (31). We have used multisection CT to evaluate these aneurysms and have found CT to be more accurate than angiography in their evaluation (Fig 16). The accurate preoperative diagnosis of the size and location of these frequently large aneurysms is important in avoiding injury during reoperative cardiac surgery.

The accurate evaluation of normal coronary artery anatomy with multisection CT has been well established. Although promising results were reported with the four-section CT scanner (32), the more recent advent of the 16-section CT scanner has further improved the sensitivity, specificity, and predictive value that can be achieved with this technique (33). We have seen a number of cases in which accurate preoperative evaluation of native coronary artery position significantly changed the surgical approach. These
cases clearly require cardiac gating, because the dynamic evaluation of the coronary arteries and their relationships to the sternum are optimally demonstrated in systole and diastole (Fig 17).

The use of cardiac gating has been particularly important in the definitive evaluation of coronary artery anatomy in patients with type A aortic dissection (34). Identification of a dissection flap that involves the coronary artery will change surgical management. In these patients who are identified preoperatively, harvesting of a saphenous vein or LIMA graft can be performed before the patient is placed on cardiopulmonary bypass for the dissection repair, which substantially decreases the “on pump” time for those people needing revascularization (Fig 18).

Congenital anomalies of the coronary arteries are rare but important findings during cardiac catheterization. They occur in 0.02% of the population and 0.1% of patients who have undergone cardiac catheterization (35). Although these anomalies were originally thought to be benign, a number of investigators have described their role in angina, myocardial infarction, and sudden death. Although magnetic resonance imaging has
been used to diagnose these anomalies (36), ECG-gated CT has become the imaging method of choice for distinguishing benign from potentially lethal variants of these congenital anomalies. We have used ECG-gated CT to define the course of these anomalous vessels, and these studies have served as the preoperative road map for revascularization in these complicated cases (Fig 19).

Conclusions
The article has presented a variety of important anatomic and pathologic examples that can be crucial to the cardiac surgeon in his or her preoperative planning for the complicated cardiac patient. ECG-gated multisection CT has proved to be a powerful and clinically important imaging method in the preoperative assessment of preoperative and reoperative cardiac surgery patients. As cardiac surgical technique becomes more sophisticated and the complexity of surgical procedures continues to grow, so will the role of multisection CT. In recognizing the important technical and anatomic challenges facing the cardiac surgeon, the radiologist can use advances in CT imaging to become an essential part of the successful care and treatment of the preoperative cardiac patient.

Acknowledgments: The authors thank Adrienne Jones for her expert assistance in the preparation of the manuscript and Joseph Molter for his technical assistance with the figures used in this article.

References
7. Stamou SC, Jablonski KA, Pfister AJ, et al. Stroke after conventional versus minimally invasive coro-


This article meets the criteria for 1.0 credit hour in category 1 of the AMA Physician's Recognition Award. To obtain credit, see accompanying test at http://www.rsna.org/education/rg_cme.html.