3

Complications of Cardiac Catheterization

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Because all cardiac catheterizations involve the insertion of foreign objects (i.e., cardiac catheters) into the circulatory system, it should not be surprising that a variety of adverse events (complications) can ensue. These complications range from minor problems with no long-term sequelae (e.g., transient bradycardia during coronary contrast injection) to major problems [e.g., cardiac perforation, abrupt closure of a coronary artery during percutaneous transluminal coronary angioplasty (PTCA)] that may require immediate surgical attention or cause irreversible damage (e.g., stroke, myocardial infarction, renal failure, or even death).

Fortunately, the risk of producing a major complication during most procedure types in current practice is generally less than 1%, a level at which the risk-benefit ratio still favors performing cardiac catheterization as part of the investigation or treatment of cardiac disorders that are themselves life-threatening or symptom-limiting. For the individual patient, the risk of sustaining a complication varies widely, depending on demographics (age, gender), the cardiac anatomy (left main coronary artery disease, severe aortic stenosis, diminished left ventricular function), the clinical situation (unstable angina, acute myocardial infarction, cardiogenic shock), and the type of procedure being performed (diagnostic catheterization, angioplasty, and so on). By considering all these factors, however, the physicians and support staff can arrive at a fairly accurate estimate of what level of risk is entailed in any given procedure. Familiarity with those risks can be of immeasurable value in the following: (a) anticipating increased risk of complication, (b) taking extra precautions to avoid them (e.g., placing a prophylactic pacemaker in a patient prior to rotational atherectomy of a right coronary artery lesion), (c) promptly recognizing complications when they occur (e.g., perforation of the right atrium during a transseptal puncture), and (d) taking corrective and potentially life-saving action (e.g., pericardiocentesis for perforation-induced tamponade).

With this knowledge, the details of the planned procedure and its anticipated risks should be discussed candidly with the patient and family. This discussion should include what procedures are planned, what benefits are hoped for, the attendant risks and their probabilities, and how the risks and benefits of the planned procedure compare with those of any possible alternatives (e.g., bypass surgery instead of coronary angioplasty). By covering these cornerstones of “informed consent” clearly and candidly, the patient and family will be realistically prepared should a complication occur. Such a discussion should be documented in the patient's chart, and that documentation should specify the type of procedure that is planned, the potential major complications, and their estimated risk of occurrence (e.g., “death, MI, or stroke < 1%, vascular injury requiring transfusion or surgical repair < 1%”).

If a significant major complication does occur, the patient and family should be told about it as soon as the procedure has been completed (or when a delayed complication occurs, as soon as it is recognized). This discussion should describe the nature of the complication (without placing blame on anyone), indicate whether any long-term consequences are expected, and outline what corrective actions have been and will be pursued. The catheterizing physician also must continue daily inpatient follow-up visits to any patient who has sustained a significant complication, since a patient's feeling abandoned by an uncaring physician tends to foster a desire for retribution (i.e., a malpractice suit).

For these reasons, all individuals performing cardiac catheterization should be intimately knowledgeable about the potential complications of the procedures they perform, as detailed in this chapter. In addition, the catheterization laboratory director should collect information about the frequency of these complications on at least a yearly basis and should review those data with the physician staff to identify where the laboratory as a whole (or an individual opera or) is performing below expected standards. We have done this yearly in our laboratory since 1987 **(1)**

following the template shown in **Table 3.1**, and we have used this analysis to guide the progressive evolution of our practice toward optimizing procedural outcome. This type of data collection, analysis (including breakdown by procedure type and by individual operator), reporting, and adjustment in laboratory policy and procedures is one of the most important jobs of any catheterization laboratory director.

SPECIFIC COMPLICATIONS

Death

Diagnostic Catheterization

Death as a complication of diagnostic catheterization has declined progressively over the last 30 years. Compared with the 1% mortality seen with diagnostic catheterization in the 1960s **(2)**, the first Society for Cardiac Angiography registry of 53,581 diagnostic catheterizations performed from 1979 to 1981 showed a 0.14% procedure-related mortality **(3)**. By the second registry of 222,553 patients catheterized from 1984 to 1987 **(4)**, procedure-related mortality had fallen slightly more to 0.1%. The small size of this reduction in mortality, however, belies the fact that the second registry included many more patients at higher risk for the procedure. If a "high-risk subgroup" is characterized using the variables identified by analyzing the 218 deaths in the second registry [age > 60, New York Heart Association (NYHA) functional class IV, left ventricular ejection fraction < 30%, or left main disease], the mortality for such patients was cut in half between the first and second registry **(5)**. A third registry of 58,332 patients studied in 1990 showed an even lower overall mortality of 0.08%, with a 1.5% incidence of any major complication **(6)**. A number of baseline variables (including NYHA class, multivessel disease, congestive heart failure, and renal insufficiency) were identified in this registry, whose presence predicted an up to eight-fold increase in major complication rates (from 0.3 in patients with none of these factors to 2.5%) **(7)**.

Although a progressive reduction in the overall mortality of diagnostic cardiac catheterization has occurred over the last 25 years, certain patient groups remain at increased risk. **Table 3.2** lists some of the most important risk factors. Patients with left main coronary disease in the 1976 report by Bourassa had a 6% mortality **(8)**. This same pattern was seen with a mortality of 2.8% for patients with severe left main disease (compared with a mortality of 0.13% in patients without such disease) in the study by Hillis and colleagues of catheterizations performed between 1978 and 1992 **(9)**. Although the mortality of such patients had fallen to 0.86% in the first Society for Cardiac Angiography registry, this was still more than 20 times higher than the 0.03% mortality seen in patients with single-vessel disease **(3)**. Since roughly 7% of patients undergoing coronary angiography in our institution have significant left main disease, the protocol used for coronary angiography (Chapter 11) begins with careful entry into the left coronary ostium to detect early recognition of left main disease through catheter pressure damping or performance of a test "puff" immediately after engagement. Even without these early warnings of left main disease, we routinely perform the first injection in the right anterior oblique (RAO) projection with caudal angulation to screen for left main disease and get the maximal anatomic information on the first injection. If ostial left main stenosis is suspected, a straight anterior (AP) injection may be performed. If severe left main disease is present, the only other injection that is needed is an RAO projection with cranial angulation (to see the left anterior descending and its diagonal branches). Performing a large number of superfluous contrast injections in a patient with a critical left main disease offers little more in the way of important anatomic information and increases the risk of triggering the vicious cycle of ischemia-hypotension-more ischemia, which may lead to irreversible collapse. Careful attention to all other aspects of technique is essential, since even an otherwise minor complication (e.g., a vasovagal reaction or arrhythmia) may have fatal consequences in such patients. If a patient with severe left main disease exhibits any significant instability during the procedure, we tend to place an intraaortic balloon pump (Chapter 21) and arrange for prompt bypass surgery. Similar considerations apply to any patient with an unstable ischemic syndrome or acute myocardial infarction who behaves in a brittle fashion under the stresses of catheter placement and contrast injection.

Patients with severe baseline left ventricular dysfunction (ejection fraction < 30%) also have a several-fold increased risk of procedural mortality **(5)**, particularly when reduction in ejection fraction is associated with a baseline pulmonary capillary wedge pressure of more than 25 mm Hg and a systolic arterial pressure of less than 100 mm Hg. An effort should generally be made to bring such congestive heart failure under control before cardiac catheterization is attempted. Right-sided heart catheterization should always be performed before angiography in a patient with poor ejection fraction, because the catheterization provides valuable data about baseline hemodynamic status and gives an

early warning about hemodynamic decompensation before frank pulmonary edema ensues. If the baseline pulmonary capillary wedge pressure is greater than 30 mm Hg, every effort should be made to improve hemodynamic status before angiography is attempted. This may entail administration of a potent intravenous diuretic (furosemide, Bumex), supplemental oxygen, a vasodilator (intravenous nitroglycerine or sodium nitroprusside) when the mean arterial pressure is greater than 65 mm Hg, or a positive inotrope (dopamine, dobutamine, milrinone) when the mean arterial pressure is less than 65 mm Hg or when severe congestive heart failure hemodynamics persist despite vasodilator treatment. When frank cardiogenic shock is present or develops during a cardiac catheterization, prompt placement of an intraaortic balloon pump in the contralateral groin may be required to get the patient safely though the procedure. More recently, percutaneous cardiopulmonary bypass (CPS) has become available for complete temporary support of the circulation in patients who experience hemodynamic collapse in the cardiac catheterization laboratory **(10)**. The ability to perform necessary angiography without precipitating hemodynamic decompensation in such unstable patients, however, has been greatly aided by the availability of low osmolar contrast agents that produce less myocardial depression than traditional high-osmolar agents (Chapter 2).

Despite the preponderance of coronary artery disease as the indication for diagnostic cardiac catheterization in the 1990s, patients with *severe valvular heart disease* are also at increased risk for dying during cardiac catheterization. The VA Cooperative Study on Valvular Heart Disease **(11)** thus showed a 0.2% mortality among 1,559 preoperative catheterizations performed in patients with valvular heart disease, with one death in a patient with mitral regurgitation and two deaths in patients with aortic stenosis. Patients who have previously undergone *coronary bypass surgery* make up a growing subgroup (up to 20% in our laboratory) of diagnostic and interventional catheterizations. They are typically 5 years older, have more diffuse coronary and generalized atherosclerosis, have worse left ventricular function, and require a more lengthy and complex procedure to image both native coronary arteries and all grafts. Despite these adverse risk factors, the Post CABG Trial **(12)** looked at 2,635 diagnostic angiograms performed in stable patients and found no mortality, and major complications in 0.7% (myocardial infarction 0.08%, stroke 0.19%, vascular trauma requiring transfusion or surgery 0.4%). *Pediatric patients* may be at higher risk (Chapter 6). One review of 4,952 patients (median age 2.9 years) studied at the Hospital for Sick Children in Toronto **(13)** found a mortality of 1.2% confined to patients under age 5 (half in critically ill neonates less than 30 days of age). Although the risk was lower for diagnostic than for electrophysiologic or interventional procedures, there were three deaths (0.1%) among the 3,149 diagnostic procedures.

There are many potential explanations for this progressive decline in the mortality of diagnostic catheterization, including improvement in catheter design (less traumatic “soft” tips), imaging systems, contrast agents, and high annual procedure volume (>1.5 million/year) and shorter procedure duration. It is less clear whether the use of heparin anticoagulation during diagnostic catheterization makes any further contribution. This was probably the case in the 1970s, when crude catheter designs and long procedure times using the femoral approach led to a higher mortality than the brachial approach **(14)**,**(15)**. Subsequent studies, performed 15 years later after the routine adoption of systemic heparinization, showed that the mortality was no higher for the femoral approach**(4,6,7)**.Some laboratories continue to use systemic heparinization routinely for diagnostic procedures, based on this circumstantial evidence. On the other hand, many laboratories currently omit heparin for femoral procedures **(16)** and report comparably low incidences of major complications. It is unlikely that this issue will be resolved by a clinical trial, since finding even a 50% treatment effect (mortality 0.2% to 0.1%) would require randomization of more than 100,000 patients. With or without heparin, however, the speed, the potential for going on to perform a broad range of interventional procedures (angioplasty, stent placement, atherectomy), and the possibility of circulatory assist (e.g., intraaortic balloon) have made the femoral approach the one preferred for cardiac catheterization in high-risk or unstable patients. The 1990 Society of Cardiac Angiography and Intervention (SCA&I) registry thus showed that 83% of diagnostic and 96% of interventional procedures were performed by the femoral approach **(6)**.

Interventional Procedures

Because they involve the use of more aggressive catheters, superselective cannulation of diseased coronary arteries, brief interruption of coronary or even systemic flow (e.g, balloon valvuloplasty, Chapter 26), interventional procedures tend to carry higher mortality than purely diagnostic catheterizations **(1)**. In the first 1,500-patient coronary angioplasty registry sponsored by the National Heart, Lung, and Blood Institute (NHLBI) from 1979 to 1982, the mortality of elective angioplasty was 1.1% **(17)**. This was relatively unchanged at 1.0% in the second NHLBI registry of 1,802 patients treated at 15 centers between 1984 and 1987, largely because the second registry included larger numbers of patients with adverse features (advanced age, poor ventricular function, multivessel

disease, prior bypass surgery, and so on) **(18)**. In fact, the mortality for single-vessel procedures fell from 1.3% to 0.2% between the first and second registry. This mortality estimate is supported by contemporaneous data from our own laboratory, showing a 0.3% overall mortality for angioplasty **(1)**, and data from Emory showing a 0.1% mortality in 3,500 patients undergoing elective coronary angioplasty in the mid-1980s **(19)**. With the introduction of newer devices (e.g., stents, atherectomy, laser) to treat high-risk lesions preemptively or reverse abrupt closure following attempted conventional balloon angioplasty, the overall mortality for elective coronary intervention has fallen further (Chapter 23), but the extension of intervention to other high-risk subsets including patients with recent (<30 days) or acute myocardial infarction may be associated with a significantly higher mortality risk than is seen in elective interventions. This has been incorporated in a multivariable model that predicts procedural mortality (range 0% to 35%) based on age, ejection fraction, treatment for AMI/shock, urgent/emergent priority, etc. **(20)**. Other specialized interventional procedures such as balloon valvuloplasty carry a risk (1% to 2% mortality) similar to that of high-risk coronary angioplasty.

Thus, although it is fair to say that the mortality of catheter-based interventional procedures is roughly 10-fold higher than purely diagnostic catheterization (i.e., 1% vs. 0.1%), there is such a wide variation in risk based on patient comorbidities, clinical indication, and procedure type that these “average” risks should only be quoted to “average” patients. Patients with one or more adverse risk factors should be told candidly during the “informed” consent process that their expected risks are somewhat higher than these averages.

Myocardial Infarction

Diagnostic Catheterization

Although transient myocardial *ischemia* is relatively common during diagnostic catheterization and occurs routinely during coronary intervention, such ischemic episodes usually respond promptly to drug therapy (intravenous or intracoronary nitroglycerine) or deflation of the angioplasty balloon. In contrast, myocardial *infarction* is an uncommon but important complication of diagnostic cardiac catheterization. In the late 1970s, data from the Coronary Artery Surgery Study showed a myocardial infarction rate of 0.25% for coronary angiography **(21)**. In the first, second, and third registries conducted by the Society for Cardiac Angiography**(3,4,6)**,the risk of myocardial infarction fell progressively, from 0.07% and 0.06% to 0.05%. This reduction relative to experience during the 1970s likely reflects greater attention to catheter flushing, pressure damping-all nuances that are now considered integral parts of coronary angiography (Chapter 11), as well as the possible benefits associated with the widespread interval adoption of systemic heparinization for coronary angiography **(22)**.

However, the risk of precipitating myocardial infarction during diagnostic catheterization is clearly influenced by patient-related (as well as technique-related) factors that include the extent of coronary disease (0.06% for single-vessel disease, 0.08% for triple-vessel disease, and 0.17% for left main disease) **(4)**, the clinical indication (e.g., unstable angina or recent subendocardial infarction), and the presence of insulin-dependent diabetes. In such higher-risk patients, avoidance of myocardial infarction again requires adequate patient preparation (e.g., institution of beta blockade, calcium channel blockers, aspirin, heparin, and supplemental oxygen) as well as meticulous attention to technical issues.

When critical lesions are identified in such unstable patients, current practice has evolved toward performing the diagnostic catheterization with “angioplasty stand-by.” If the diagnostic angiogram shows a severe coronary lesion for which a catheter intervention (e.g., angioplasty, atherectomy, stenting) is appropriate, the interventional procedure is then performed in the same sitting. This is true particularly if the patient exhibits clinical instability (including prolonged ischemia with reduced flow or occlusion of a coronary artery) that might signal the transition to myocardial infarction. On the other hand, if angiography reveals anatomy that is better suited for bypass surgery, patients with severe unstable angina should have an intraaortic balloon placed or should at least remain on intravenous heparin (sometimes leaving the vascular sheaths in place) while awaiting surgery. In particular, unstable patients should not have their heparinization reversed by protamine (which may trigger ischemia or frank infarction in an unstable patient), absent a life-threatening bleeding complication. If sheath removal is desired, the heparin infusion can be reduced or interrupted for several hours (until the Activated Clotting Time [ACT] falls below 160 seconds), and then restarted 2 hours later.

Although myocardial infarction may occur in the hours following catheterization (particularly in unstable patients whose lesions and anticoagulant status are not managed aggressively), postprocedure myocardial infarction is rare in elective patients who complete their catheterization procedure without demonstrating signs of instability (e.g., severe or prolonged angina). Elective diagnostic procedures in such individuals are thus now routinely performed on an outpatient basis **(23)**, although roughly one-third of patients preselected for the outpatient approach will require hospital admission based on their anatomic findings, clinical instability, or complications that develop during or following the procedure. For unstable patients (or those who are hospitalized based on anatomic findings or instability during what had been planned as an outpatient procedure), we recommend serial electrocardiogram (ECG) and creatine phosphokinase (CPK) surveillance (immediately after the procedure and again on the following morning). Since CPK may leak from skeletal sources following catheterization and groin compression, measurement of the cardiospecific MB fraction (CK-MB) is also advisable **(24)**.

Should severe ischemic instability develop after the patient leaves the catheterization laboratory, aggressive therapy is indicated. Since the coronary anatomy is known, physicians should consider bringing the patient back to the laboratory for either coronary angioplasty or intraaortic balloon pump placement followed by urgent bypass surgery. It is usually appropriate to reinstitute heparinization, maximize medical therapy (including intravenous nitroglycerine), and administer narcotics to relieve pain and attenuate the consequent sympathetic nervous system response. If urgent catheter-based intervention (rather than bypass surgery) is chosen, consideration should also be given to administration of one of the IIb/IIIa receptor blocker antiplatelet agents (see later) to help facilitate restoration of adequate perfusion and enhance the safety of the planned urgent intervention. We prefer the IIb/IIIa blockers (particularly short-acting small molecules such as Integrilin and Aggrastat) to intravenous thrombolytic therapy for this indication, although the thrombolytic approach may still be appropriate if the patient has ongoing ST-segment elevation, the hospital does not perform coronary intervention, and transfer to a neighboring hospital with that capability is expected to take more 90 minutes.

Interventional Procedures

Coronary interventions may produce myocardial infarction by a variety of mechanisms that include dissection, abrupt vessel closure, “snow-plow” occlusion of side branches, spasm of the epicardial or arteriolar vessels (“no-reflow”), thrombosis, or distal embolization (Chapter 23). In the initial angioplasty experience, myocardial infarction was seen in about half of the 6% of patients who were sent to emergency bypass surgery for abrupt vessel closure **(17)**. Q-wave myocardial infarctions were thus reported in 4.8% of patients in the first NHLBI registry and in 3.6% in the second NHLBI registry **(18)**. The current experience with balloon angioplasty and newer devices suggests that emergency bypass surgery and Q-wave infarction rates have each fallen to roughly 1% (Chapter 23).

Although infarction due to emergency surgery has decreased, the higher proportion of complex lesions (including saphenous vein grafts), treatment of patients with unstable syndromes, and use of more aggressive stent and atherectomy devices has made it clear that at least 20% of patients experience some increase in CK-MB fraction after an otherwise successful intervention. Some elevation of CPK and CPK-MB (generally without associated ST- or T-wave electrocardiographic changes) may be seen in 5% to 10% of otherwise successful balloon angioplasties **(25)** and as many as 15% to 20% of procedures performed with new devices (particularly directional, rotational, or laser atherectomy) **(26)**. Patients with these low-level enzyme elevations are more likely to have some degree of chest discomfort, although this finding is common also in patients without enzyme elevation, where it presumably represents stimulation of adventitial pain receptors by local stretching at the treatment site **(27)**. Careful review of the cineangiograms sometimes shows compromise of a small side branch originating in the area of a treated lesion.

Considerable debate exists about the meaning of such CK elevations in patients who have had otherwise successful interventional procedures. Our initial observations suggested that low order (one to three times the upper limit of normal) appears to have no short- or long-term consequences and that only elevation above five times normal (i.e., CK-MB > 50 IU/L in a laboratory with an upper limit of normal of 10 IU/L) tends to adversely impact late survival **(26)**. We therefore suggested that only these larger elevations of enzymes should be viewed as a major complication of coronary intervention, equivalent to Q-wave myocardial infarction. This analysis has been challenged by long-term follow-up of patients from other centers and trials **(28)**, where patients with even low-level elevation of postprocedural CK have been found to have greater incidences of long-term (3- to 5-year) adverse outcomes, which (varying from study to study) may include late death, late myocardial infarction, or late repeat revascularization. The

question of whether any such relationship is “cause-and-effect” or simply an association of both periprocedural CK elevation and late events with a common “confounding variable” (such as the diffuse underlying atherosclerosis) is still being debated **(29)**. If the relationship were cause-and-effect, randomized trials comparing procedures such as atherectomy (that have substantially higher incidences of CK elevation to conventional balloon angioplasty) *should* show worse late outcomes concentrated among the patients with CK elevation, whereas randomized trials comparing agents such as the IIb/IIIa blockers (which are effective in lowering the incidence of periprocedural CK elevation) should show consistent reductions in these late outcomes. Neither has yet been demonstrated **(30)**,**(31)**. Absent finding differential mortality which parallels the frequency of CK elevations in such randomized trials (that match the groups for all other variables, including the diffuseness of atherosclerosis), a more likely explanation is that postprocedural CK elevation is a surrogate marker for diffuse atherosclerosis, not the proximate cause of subsequent adverse events. The answer about causality is important since the main effect of IIb/IIIa receptor blockers on the composite endpoint (death, any infarction, repeat revascularization) has been on non–Q-wave infarction. Until conclusive data are available, we tend to use these agents to prevent closure in vessels with an imperfect mechanical result from intervention or intraprocedural thrombus, rather than as an across-the-board way to reduce the incidence of (non–Q-wave) myocardial infarction. Of course other potent oral antiplatelet agents (e.g., ticlopidine, clopidogrel) work indirectly through the ADP receptor to decrease IIb/IIIa receptor expression on the platelet surface and have many similar effects. They have become part of the standard adjunctive therapy in coronary stent placement and may play an increasing role in all coronary interventions.

Cerebrovascular Complications

Cerebrovascular accidents (strokes) are uncommon but potentially devastating complications of diagnostic cardiac catheterization. Early experience showed an incidence as high as 0.23% in the 1973 study of Adams **(15)**, compared with the 0.07% incidence for the more recent diagnostic catheterizations included in the Society for Cardiac Angiography registries **(3)**,**(4)**. Although their incidence has decreased, strokes are potentially one of the most devastating complications of cardiac catheterization, and every operator should be familiar with potential etiologies, preventive strategies, and treatments for catheterization-related stroke. It is also a good idea to speak with the patient directly at the end of the procedure and to have a low threshold for performing a screening neurologic exam if the patient is less alert, has slurred speech, and has either visual, sensory, or motor symptoms during or after a left heart procedure.

Catheterization-related strokes are almost always embolic in origin. There is come evidence that many such emboli are dislodged from unsuspected aortic plaque or diffuse atherosclerosis, given the observation that atherosclerotic debris is liberated from the wall of the aorta in 40% to 60% of cases during advancement of large-lumen guiding catheters over a 0.035-inch guidewire. This supports the observation that most strokes and neuroophthalmologic complications (i.e., retinal artery embolization) appear to be caused by emboli released by disruption of unrecognized plaques on the walls of the aorta, liberating cholesterol crystals, calcified material, or platelet-fibrin thrombus into the aortic root**(32-34)**. End-hole (i.e., coronary angiographic or particularly guiding) catheters should thus be introduced over a guidewire to the level of the tracheal carina (descending aorta) and flushed carefully **(35)**. The catheters should then be advanced around the aortic arch smoothly without excessive “catching” in surface features that may suggest the presence of such friable plaques. If any such problems are noted during catheter advancement, the catheter should be pulled back into the descending aorta, double-flushed, and then readvanced around the arch over a leading J-tip guidewire. In fact, many operators now routinely take the left Judkins catheter around the arch over the guidewire before flushing and clearing with contrast (Chapter 4). It is still not clear whether the benefit of advancement over a guidewire completely offsets the risk of introducing debris, clot, or air into the aortic root while performing the first catheter flush there rather than in the descending aorta.

While many or even most cerebral emboli during left heart catheterization appear to come from unintentional trauma to preexisting atherosclerotic aortic plaques, the operator needs to take into account the potential to cause similar central nervous system (CNS) embolic problems by technical errors. These may involve sloppy catheter flushing, introduction of air bubbles during contrast injection, inadvertent placement of wires and catheters into the arch vessels, prolonged (>3-minute) “wire dwell times” during attempts to cross a stenotic aortic valve, and failure to carefully wipe and immerse guidewires in heparinized saline before their reintroduction during left-sided heart catheterization. Avoidance of the arch vessels is probably even more important in patients with known cerebrovascular disease or bruits over the carotid or subclavian arteries. Even in patients without carotid bruit or

previous stroke, any carotid manipulation (including *external* carotid sinus massage) carries a risk of precipitating a neurologic complication.

Embolic material may also originate in the cardiac chambers, thrombotic coronary arteries, or surface of cardiac valves. One should thus avoid placing the pigtail catheter fully out to the left ventricular apex in patients with suspected aneurysm or recent myocardial infarction, since either condition may be associated with potentially dislodgeable mural thrombus. Cases have also been reported wherein clot contained in an occluded native coronary artery or vein graft was inadvertently withdrawn or propelled out of that vessel, and into the aortic root during attempted coronary intervention or forceful injection of contrast through a distal superselective catheter **(36)**. Care must also be taken to avoid transseptal catheterization or mitral valvuloplasty in patients with left atrial thrombus, which may increase the incidence of clinical stroke. One study that showed an unexpectedly high incidence of new hyperintense brain lesions by magnetic resonance imaging (MRI) after percutaneous balloon mitral valvuloplasty **(37)**, suggests that small subclinical emboli may occur more commonly than previously suspected. In patients with right-to-left shunting (including atrial septal defects with Eisenmenger physiology, but also patients with right ventricular infarction and a patent foramen ovale), paradoxical embolization may also lead to stroke. In such patients, the same level of care regarding flushing catheters and sheaths that is routine during left heart procedures should also be extended to right heart procedures.

The question of embolic risk also invariably comes up when it is necessary to perform catheterization on patients with endocarditis of left-sided (aortic and mitral) heart valves. On the one hand, the associated vegetations look friable and can embolize spontaneously. On the other hand, they have already withstood repeated trauma from opening and closing of the affected valves without dislodgment. In a series of 35 patients with active endocarditis who underwent left-sided cardiac catheterization (five of whom had prior spontaneous systemic emboli), not one had a catheterization-induced embolic event **(38)**. This supports the view that left-sided cardiac catheterization can be performed safely in patients with active endocarditis for whom surgical intervention is being considered.

Other than cerebrovascular emboli from intracardiac, arterial, or catheter sources, patients receiving aggressive anticoagulation, antiplatelet, or thrombolytic therapy are also prone to spontaneous intracerebral bleeding as a potential cause for postprocedure neurologic complications. If any doubt exists, and particularly if thrombolytic therapy or intensive anticoagulation are being considered as treatment for a presumptive cerebrovascular embolus, neurologic consultation and computerized tomography (CT) or MRI scanning are advisable. The distinction is critical, since there have been reported cases of resolution of embolic strokes that occurred during cardiac catheterization after selective infusion of a thrombolytic into the occluded cerebral vessel **(36)**, and successful treatment of patients with posterior fossa bleeds as the result of prompt recognition and neurosurgical evacuation. If no embolic or hemorrhagic etiology is apparent, it is helpful to recall that transient neurologic deficits have also been reported following the injection of high-osmolar-contrast agents into the carotid or vertebral arteries. Use of low-osmolar agents (Chapter 2) is thus required for internal mammary angiography, both to avoid cerebral contrast toxicity and to minimize the intense pain associated with the injection of high-osmolar contrast into the internal mammary artery.

Local Vascular Complications

Local complications at the catheter introduction site are among the most common problems seen after cardiac catheterization procedures, and probably the single greatest source of procedure-related morbidity. These problems include vessel thrombosis, distal embolization, dissection, or poorly controlled bleeding at the puncture site. Ongoing bleeding may be due to a poorly placed puncture, vessel laceration, excessive anticoagulation, or poor technique in either suture closure (brachial approach) or groin compression (femoral approach). In the femoral approach, poorly controlled bleeding may present as free hemorrhage, femoral or retroperitoneal hematoma, false aneurysm, or arteriovenous fistula. Hemorrhage and hematoma are generally evident within 12 hours of the procedure, but the diagnosis of false aneurysm may not be evident for days or even weeks after the procedure. Given the common and troublesome nature of postprocedure vascular complications, all cardiac catheterization operators must understand vascular access and closure techniques completely, to recognize and treat each type of complication.

Diagnostic Catheterization

In the early experience with brachial cutdown, Machleder reported a 5.4% incidence of brachial reexploration, predominantly for loss of the distal radial arterial pulse following the procedure **(39)**. Early experience with the femoral approach by Judkins reported a 3.6% local complication rate **(40)**. In contrast, the more recent Society for Cardiac Angiography registries reported a 0.5% to 0.6% incidence of vascular complication for diagnostic catheterization, which was similar for the brachial and femoral approaches **(6)**. In keeping with these early experiences, however, brachial complications still tend to be thrombotic, and femoral complications are more likely to be hemorrhagic. Because they are fundamentally different, the vascular complications of these two approaches will be discussed separately.

Brachial Approach

With the brachial approach, arterial thrombosis accounts for the great majority of local complications (Chapter 5). These complications often relate to formation of a thrombus in the proximal arterial segment during the catheterization procedure and failure to effectively remove this thrombus prior to arterial repair. This can usually be accomplished by allowing brief brisk bleeding from each end of the incised brachial artery in turn. Although most operators reserve use of a Fogarty balloon embolectomy catheter to patients in whom such bleeding fails to occur or in whom a weak pulse is still present after arteriotomy repair, another approach is to routinely pass the Fogarty catheter and instill a heparin solution into the proximal and distal arterial segments to prevent thrombus formation just prior to arterial repair **(41)** to effectively prevent this complication. Brachial arterial thrombosis may also develop secondary to an intimal flap within the arterial lumen that has not been properly “tacked down” or removed at the time of arterial repair, creating a pocket of stasis where thrombus can accumulate. Occasionally, local arterial spasm may develop in the hours immediately following catheterization and successful arterial repair, resulting in secondary arterial thrombosis that can convert an initially bounding radial pulse into one that is weak or absent 6 hours after catheterization.

Prevention of brachial artery thrombosis can best be accomplished by meticulous attention to the details of arterial repair, which are discussed in Chapter 5. Adequate heparinization includes systemic administration of heparin (5,000 units intravenously) shortly after initial arterial entry and local administration of heparin (1,000 to 1,500 units into both proximal and distal arterial segments) at the time of arterial repair. Inspection of the arteriotomy site, trimming of any free intimal flaps, and avoidance of arterial narrowing (as frequently occurs with a purse-string closure) will minimize arterial thrombosis. Anticoagulation is not reversed with protamine at the end of a brachial catheterization; if the arterial repair has been done properly, no local bleeding should occur.

Correction of brachial arterial thrombosis requires reexploration of the arm incision with repeat brachial arteriotomy, Fogarty catheter thrombectomy, and arterial repair **(42)**. Although a vascular surgeon usually performs this procedure in the operating room, cardiologists experienced with the brachial approach may carry out such corrective procedures in the catheterization laboratory. Successful treatment of brachial artery thrombosis by percutaneous transluminal angioplasty from the femoral artery has also been described.

Other potential local complications of brachial arterial catheterization include injury to the median nerve during cutdown and isolation of the artery, delayed dehiscence of arterial sutures with late arterial bleeding, bacterial arteritis, and local cellulitis-phlebitis associated with the cutdown itself. Injury to the median nerve is rare and should not occur if the dissection is careful. Rarely, postcatheterization bleeding within the brachial wound may lead to hematoma formation and compression of the nerve. This responds to prompt evacuation of the hematoma. Mild injury to the median nerve results in numbness and weakness of the thenar aspect of the hand, which almost always returns to normal within 3 to 4 weeks, although occasionally some neurologic symptoms may require up to 6 months for complete resolution. Local cellulitis-phlebitis is most likely to occur if (a) extensive soft tissue is dissected during the brachial cutdown; (b) large veins are used and tied off; (c) the catheterization procedure is long; (d) seroma or hematoma forms in the incision; (e) nonviable tissue (e.g., fat deprived of its blood supply) is left in the incision; and (f) poor surgical technique or violation of sterile procedure occurs. The routine use of a potent germicidal agent (e.g., 1% povidone-iodine solution) for wound irrigation prior to skin closure substantially reduces the incidence of infection. Routine cases do not require prophylactic antibiotics, but antibiotics should be used any time a high probability of wound infection exists (e.g., a long procedure in which a known breach of sterile technique occurred). In such instances, oxacillin 500 mg by mouth (PO) every 6 hours for 5 days beginning at the time of wound closure (initial loading dose given intravenously) is generally adequate.

Femoral Approach

Femoral artery thrombosis is extremely rare, except in patients with a small common femoral artery lumen (peripheral vascular disease, diabetes, female gender), in whom a large-diameter catheter or sheath (e.g., an intraaortic balloon pump) has been placed, particularly when the catheter dwell time is long. Such patients may complain of leg pain or numbness and have diminished distal pulses during the catheterization procedure, if the diagnostic sheath itself obstructs antegrade flow and adequate collaterals are not present. This type of obstructive limb ischemia generally resolves and distal pulses return promptly when the sheath is removed at the end of the procedure. Patients who have ongoing complaints and diminished or absent distal pulses that fail to resolve with catheter removal (or who develop such findings in the hours after catheterization) may have flow-obstructing dissection or thrombus at the femoral artery puncture site, or a distal arterial embolus. This requires urgent vascular surgery consultation with exploration for local dissection or plaque avulsion, and Fogarty embolectomy of the distal vessel as needed to restore distal pulses. Failure to do so promptly (generally within 2 to 6 hours) may result in extension of thrombosis into smaller distal branches, with attendant muscle necrosis that may necessitate fasciotomy or even amputation.

Femoral venous thrombosis or *pulmonary embolism* are rare complications of diagnostic femoral catheterization. A small number of clinical cases have been reported, however, particularly in the setting of venous compression by a large arterial hematoma, or prolonged procedures with multiple venous lines (e.g., electrophysiologic studies) **(43)**. The actual incidence of thrombotic and pulmonary embolic complications may, however, be substantially underreported, since most are not evident clinically. Asymptomatic lung scan abnormalities have thus been described in up to 10% of patients after diagnostic catheterization **(44)**. One series of endomyocardial biopsy procedures reported a similarly high incidence of echocardiographic detection of thrombi passing through the right-sided heart chambers, particularly when the venous sheath was not aspirated and flushed between insertions of the bioptome **(45)**. To avoid this problem, we attach a continuous drip of heparinized saline to the venous sidearm throughout the catheterization procedure to reduce the chance of clot formation within (and embolization from) the lumen of the venous sheath.

A more common problem after cardiac catheterization by the femoral approach relates to poorly controlled bleeding from the arterial puncture site **(46)**. Uncontrollable free bleeding around the sheath suggests *laceration* of the femoral artery. If such free bleeding does not respond to replacement with the next-larger-diameter sheath, the bleeding should be restricted by manual compression around the sheath until the procedure is completed. Heparin should then be reversed, and an attempt may be made to remove the sheath and control bleeding with prolonged (30- to 60-min) compression, either manually or with a compression device (see Chapter 4). Blood for transfusion should be typed and cross-matched, and the vascular surgeons should be consulted regarding operative repair should the bleeding continue.

More common than free bleeding is the formation of a *hematoma*-a collection of blood within the soft tissues of the upper thigh that causes a tender baseball- or softball-sized mass. If ongoing bleeding stops with manual compression, the hematoma will usually resolve over 1 to 2 weeks as the blood gradually spreads and is reabsorbed from the soft tissues. Instances of femoral nerve compression from groin hematomas, however, may lead to quadriceps weakness that may take weeks or even months to resolve. Larger hematomas may require transfusion, but surgical repair for hematoma (as opposed to false aneurysm) is generally not required. Given the discomfort caused by large hematoma and the potential of such hematoma to evolve into false aneurysms, accurate puncture and puncture site compression technique to minimize hematoma formation are essential parts of good catheterization technique.

If the arterial front (or back) wall puncture was made above the inguinal ligament, a hematoma may extend into the retroperitoneal space. Such bleeding is not evident from the surface, but should be considered whenever a patient develops unexplained hypotension (particularly if it responds only briefly to aggressive volume loading), fall in hematocrit, or ipsilateral flank pain following a femoral catheterization procedure. The diagnosis may be confirmed by CT scanning or abdominal ultrasound, but the treatment is usually expectant (transfusion, bedrest) rather than surgical. The best prevention for retroperitoneal bleeding is careful identification of the puncture site, to avoid entry of the common femoral near or above the inguinal ligament. Effective catheter-based interventions have yet to be developed, but localization and occlusion of a retroperitoneal bleeding site using a peripheral angioplasty balloon have been reported **(47)**.

If a hematoma remains in continuity with the arterial lumen (due to dissolution of the clot plugging the arterial puncture site), a *pseudoaneurysm may develop* (Fig. 3.1). Blood may flow in and out of the arterial puncture, expanding the hematoma cavity during systole and decompressing back into the arterial lumen in diastole. Since the hematoma cavity contains no normal arterial wall structures (i.e., media or adventitia), this condition is referred to as false or pseudoaneurysm. On physical examination, it can be distinguished from a simple hematoma by the presence of pulsation and an audible bruit over the site. Duplex ultrasound scanning is confirmatory **(48)**. Since all but the smallest (< 2 cm in diameter) false aneurysms tend to enlarge and ultimately rupture, we usually have the vascular surgeons repair them (generally under local anesthesia) when they are detected **(46)**. Repair is almost certain to be required if the patient needs to take oral anticoagulant medication (i.e., warfarin) after the procedure. More recent alternatives to vascular surgical repair include the use of an ultrasound transducer to compress the narrow "neck" through which blood exits the femoral artery for 30 to 60 minutes, which may permanently close the track and eliminate the need for surgery **(49)**. It may also be possible to inject the false aneurysm cavity with procoagulant solutions or embolization coils during ultrasound-guided occlusion of the aneurysm neck. False aneurysms smaller than 2 cm in diameter may be followed expectantly, with up to half closing before a 2-week follow-up ultrasound **(50)**. Those that persist or cause symptoms should probably be repaired surgically.

FIG. 3.1.

Common significant femoral vascular complications. **Top left:** Angiographic appearance of a false aneurysm of right femoral artery *(arrow)* that developed 4 to 5 days after percutaneous retrograde femoral arterial catheterization complicated by a significant local hematoma after groin compression. Note that the arterial puncture had been made in the superficial (rather than common) femoral artery. **Top right:** Schematic diagram showing the surgical approach to the false aneurysm cavity and the underlying puncture. **Bottom left:** Angiographic appearance of an arteriovenous fistula with simultaneous filling of the femoral artery (left) and vein (right). **Bottom right:** Diagram showing the potential anatomic situations (overlying arterial and venous branches) that may underlie fistula formation after femoral puncture. (From Skillman JJ, Kim D, Baim DS. Vascular complications of percutaneous femoral cardiac interventions. *Arch Surg* 1988;123:1207).

The keys to avoiding pseudoaneurysm formation are accurate puncture of the common femoral artery and effective initial control of bleeding after sheath removal. Although not confirmed in all studies, our experience suggests that punctures of the superficial femoral or profunda artery (i.e., puncture below the bifurcation of the common femoral) are significantly more likely to lead to false aneurysm formation because of the smaller caliber of the artery and the lack of a bony structure against which to compress after sheath removal **(51)**. Fluoroscopic localization of the skin nick to overlie the inferior border of the femoral head effectively avoids this error (see Chapter 4). Effective initial control is also essential, since allowing a hematoma to form makes effective control more difficult and initiates natural thrombolytic activity in the hematoma that may dissolve the early fibrin plug at the puncture site.

Ongoing bleeding from the femoral puncture site may decompress into an adjacent venous puncture site to form an *arteriovenous fistula*(Fig. 3.1)This can be recognized by a to-and-fro continuous bruit over the puncture site. Like pseudoaneurysms, arteriovenous (AV) fistulas may not be clinically evident for days after a femoral catheterization procedure **(52)**. These fistulas tend to enlarge with time, and if they do not close within 2 to 4 weeks, we refer these patients for surgical repair. The most common findings at surgery are a low puncture (i.e., of the superficial femoral or profunda, transecting a small venous branch), emphasizing the importance of careful puncture technique in avoiding this femoral vascular complication.

Interventional Procedures

Interventional procedures are almost invariably performed by the femoral approach (96% of interventional cases in the 1990 SCA&I registry were so performed) **(6)**, with a higher level of anticoagulant and antiplatelet therapy, and hence are susceptible to the predominantly hemorrhagic complications described earlier for transfemoral diagnostic catheterization. All reports thus suggest a significantly higher incidence of significant local vascular complications (those requiring surgery or transfusion, 2% to 5%) for interventional procedures than for purely diagnostic catheterization **(1)**,**(53)**. During the era when uninterrupted transition from intravenous heparin to oral warfarin was used for stenting (1990 to 1996), vascular complications after stenting were as high 10% (see Chapter 25). There

were several contributors, including the use of a larger (9F) sheath, the intensity and duration of anticoagulation, and removal of the sheaths only after an overnight dwell **(54)**. Vascular complications were also greater in women and the elderly. In addition to issues relating to puncture technique, sheath size, level of anticoagulation, and patient-related factors, the incidence of femoral vascular complications clearly depends on the timing and the technique used for sheath removal. Thus even before the switch to less aggressive anticoagulant protocols (aspirin and ticlopidine) and second-generation stents that permit use of smaller sheath size, withholding postprocedure heparin until same-day sheath removal (guided by fall in the ACT to less than 160 seconds), reduced the incidence of hemorrhagic access site complications after stenting to 1% to 2%.

Although the mainstay of sheath removal has been manual compression until hemostasis is achieved, the rapid increase in interventional procedure volume has made less labor-intensive approaches essential. Demonstrating that they produce fewer major complications than manual compression has been difficult. One exception may be mechanical or hydraulic devices that can apply local pressure that simulates mechanical compression. In one 778-patient randomized trial **(55)** comparing a clamp device with manual compression after catheter-based intervention (predominantly 8F sheath size), the incidence of potential complications by physical exam was equal (mostly ecchymoses or small hematomas). When subjected to ultrasound examination, the incidence of larger hematoma (2% vs. 4%), pseudoaneurysm (1% vs. 3%), and arteriovenous fistula (0 vs. 1%) tended to be lower with the mechanical compression. We tend to use mechanical compression devices for removal of most postinterventional sheaths, with the caveat that they must be applied correctly (so as to control the puncture site without prolonged [>3 minutes] occlusion of distal flow) and monitored continuously until control is obtained. They should also be avoided in patients at higher risk of femoral thrombosis due to severe peripheral vascular disease, or prior aorto-femoral or fem-popliteal bypass surgery. Nor do we use mechanical compression devices in patients having diagnostic or interventional procedures with smaller (e.g., 6F) sheaths, where 15 minutes of manual compression is usually adequate.

Given the ongoing incidence of complications relating to management of the arterial entry site, alternative management strategies continue to be investigated. Various approaches for collagen plugging or percutaneous suture-mediated closure of the femoral arterial puncture site have been introduced in the last several years (see Chapter 4). Although these devices avoid the discomfort of prolonged manual or mechanical compression and allow earlier or even immediate ambulation, clinical trials have failed to demonstrate significant reduction of major vascular complications compared with compression. Ultimately, it is likely that this class of devices will improve sufficiently to make closure of the femoral artery puncture site so reliable as to eliminate the 1% to 2% incidence of complication. Until then, problems must be repaired when they occur, or operators must be prepared to work from other access sites such as the radial artery (where hemorrhagic complications are unheard of, and thrombosis [with a negative Allen test] is usually inconsequential) **(56)**.

Arrhythmias or Conduction Disturbance

A variety of cardiac arrhythmias (tachy- or bradycardia) or conduction disturbance may occur during the course of diagnostic or therapeutic cardiac catheterization. Most, like ventricular premature beats (VPBs) during catheter entry into the right or left ventricle, are devoid of clinical consequence. Others, like asystole or ventricular fibrillation, pose immediate risk. Finally, some rhythm disturbances (like atrial fibrillation) are well tolerated in most patients but may trigger profound hemodynamic decompensation in patients with severe coronary disease, aortic stenosis, or hypertrophic cardiomyopathy by excessively increasing heart rate or eliminating the atrial “kick” needed to maintain diastolic filling of a stiff left ventricle.

An important part of safe cardiac catheterization is thus for the operator and the nurses/technicians to monitor the surface electrocardiogram on the same physiologic monitor used to display the pressure tracings. The monitoring equipment should also generate an audible beep with each QRS complex, to serve as another channel of information while the operator is intent on watching the fluoroscopic image. In our laboratory, the technicians are trained to call out any disturbance in rhythm such as ventricular premature beats (“Vs, running Vs, change in complex”) that may otherwise escape the operator's attention. The tools to treat these rhythm disorders-including a defibrillator capable of synchronized or asynchronous countershock, temporary transvenous pacing leads and pacemaker generator, and full array of antiarrhythmic drugs-must be immediately accessible in any cardiac catheterization laboratory **(57)**. Promptly recognizing and reversing major rhythm disturbances (e.g., by promptly countershocking ventricular

fibrillation, sometimes even before the patient fully loses consciousness) can avoid progression to full cardiopulmonary arrest that would require the institution of cardiopulmonary resuscitation (CPR). All cardiac catheterization personnel, however, must be fully certified in Advanced Cardiac Life Support (ACLS) and should be prepared to institute ventilatory and circulatory support without delay when necessary.

Ventricular Fibrillation

Ventricular ectopy or even brief (three- to five-beat) runs of ventricular tachycardia are not uncommon during passage of catheters into the right or left ventricle. Even balloon-flotation right heart catheterization may cause such brief runs of ventricular tachycardia in up to 30% of patients, with sustained ventricular tachycardia in 3% and ventricular fibrillation in 0.7% of cases **(58)**. This emphasizes the importance of controlling the catheter position in the right ventricle, and smooth passage through the right ventricular outflow tract; similar issues relate to careful positioning of the pigtail catheter free in the mid-portion of the left ventricle (see Chapter 12). If a sudden increase in ectopic activity is noted or if a run of ventricular tachycardia is initiated, the offending catheter must be repositioned immediately so that baseline cardiac rhythm is restored. The same holds true for ventricular ectopy precipitated when the tip of a guidewire is placed into a small intramyocardial branch (usually a septal branch of the left anterior descending) during coronary intervention. The guidewire should be withdrawn slightly and repositioned in the main vessel. Other than these mechanical stimuli, ventricular fibrillation can also be induced by catheter transmission of "leakage" electrical currents into the heart **(57)**,**(59)**. This problem has been effectively eliminated, however, by the adoption of standards for grounding systems in the cardiac catheterization laboratory that ensure a maximum leakage current of 20 μA between any two exposed conductive sources.

Although ventricular tachycardia and ventricular fibrillation may result from excess catheter manipulation, they more commonly result from intracoronary contrast injection. This is seen most commonly with injection of ionic (high-osmolar) contrast agents into the right coronary artery, particularly if the injection is prolonged or the catheter pressure is partially damped (see Chapter 11). Changes in injection technique and the formulation of contrast agents used for coronary angiography have progressively reduced the incidence of this complication from 1.28% in the 1973 publication of Adams **(15)** to 0.77% in the 1970 to 1974 series from the Montreal Heart Institute **(8)**, to less than 0.4% in the Society for Cardiac Angiography registry **(6)**. The incidence of ventricular fibrillation may be somewhat higher in patients with baseline prolongation of the QT interval **(60)**. Some reduction in fibrillation has been reported with use of atropine pretreatment **(61)**, but we do not routinely pretreat with atropine to avoid precipitating sinus tachycardia and ischemia in our predominant unstable angina patient population.

Some of the most refractory ventricular ectopy is seen in the setting of profound transmural ischemia or early myocardial infarction. Such ectopy may respond to loading with intravenous lidocaine (1.5 mg/kg over 1 minute, with a second bolus of 0.75 mg/kg 7 minutes later) or procainamide (15 mg/kg over 20 minutes, watching for fall in blood pressure or broadening of QT or prolongation of QRS intervals). If ectopy progresses to ventricular fibrillation, or particularly if it recurs shortly after defibrillation, intravenous amiodarone, 5 mg/kg over 20 minutes, followed by a drip of 1 g/24 hours, and additional boluses of 150 mg over 10 minutes for breakthrough ectopy may be life-saving. Amiodarone is so lipid soluble that it must be combined with a detergent (Tween-80), which may cause arterial hypotension **(62)**. The administration rates of amiodarone may thus need to be reduced or the infusion suspended if the blood pressure drops below desirable levels.

Atrial Arrhythmias

Atrial extrasystoles are common during catheter advancement from the right atrium to the superior vena cava, or during looping of the catheter in the right atrium to facilitate passage in a patient with enlargement of the right-sided heart chambers. These extrasystoles usually subside once the catheter is repositioned but may go on to atrial flutter or fibrillation in sensitive patients. Both rhythms tend to revert spontaneously over a period of minutes to hours but may require additional therapy if they produce ischemia or hemodynamic instability. Atrial flutter can be treated by a brief (15-second) but rapid (300- to 400-beats-per-minute) burst of right atrial pacing, following which reversion to sinus rhythm or onset of atrial fibrillation (with a more controlled ventricular response) can be expected **(63)**. Care must be taken, however, to ensure a stable atrial pacing location, since catheter migration into the ventricle during burst pacing may trigger ventricular fibrillation.

Atrial fibrillation is generally benign during catheterization but may cause clinical sequelae if the ventricular response is rapid (>100) or if the loss of the atrial kick causes hypotension in a patient with mitral stenosis, hypertrophic cardiomyopathy, or diastolic left ventricular dysfunction. If tolerated poorly in such individuals, atrial fibrillation or flutter may require DC cardioversion. If no significant hemodynamic dysfunction occurs, intravenous beta blockers [propranolol (Inderal, Wyeth-Ayerst, Philadelphia, PA)] 1 mg or esmolol **(64)** [Brevibloc (Baxter, New Providence, NJ)] at a loading dose of 500 μg/kg per minute for 30 seconds, followed by an infusion of 50 to 250 μg/kg per minute), or a calcium channel blocker (verapamil 5 mg) may be given and up-titrated until adequate control of the ventricular response is achieved. Once the ventricular response is controlled, chemical conversion to normal sinus rhythm can usually be accomplished by administration of intravenous procainamide (15 mg/kg over 20 minutes). Alternatively, the new class III antiarrhythmic drug ibutilide **(65)** can provide prompt conversion of new-onset atrial fibrillation or flutter. Because it may cause QT prolongation and torsade, it should not be given to patients who are on other QT-prolonging drugs or have reduced potassium or magnesium concentrations, bradycardia, or baseline QTc intervals exceeding 440 msec. In patients weighing more than 60 kg it is given as one vial (1 mg) over 10 minutes, monitoring for conversion or adverse effects (QT prolongation of ventricular ectopy). The patient should be monitored and no other type III agents should be given for 4 hours if ibutilide is administered. If there is significant hemodynamic instability from either atrial flutter or atrial fibrillation, however, the most rapid and reliable therapy is synchronized cardioversion (starting at 35 to 50 W-sec, after appropriate intravenous sedation). In patients with a history of atrial arrhythmia (frequent atrial premature contractions, paroxysmal atrial fibrillation) a single dose of quinidine or procainamide 1 to 2 hours before the procedure may help prevent atrial fibrillation.

Bradyarrhythmias

Transient slowing of the heart rate occurs commonly during coronary angiography, particularly at the end of a right coronary artery injection performed using ionic (high-osmolar) contrast agents. Since forceful coughing helps to clear contrast from the coronaries, support aortic pressure and cerebral perfusion during asystole, and restore normal cardiac rhythm, patients should be warned at the beginning of the procedure that they may be asked to cough forcefully and that they must do so without hesitation when asked. Having the nurses, technicians, and physicians all simultaneously yell “cough” when asystole develops at the end of a coronary injection is one of the most reassuring evidences of a well-trained and alert catheterization laboratory staff!

When bradycardia is more prolonged, other etiologies must be suspected. Vasovagal reaction, in which bradycardia is associated with hypotension, nausea, yawning, and sweating, is one of the more common complications (with a roughly 3% incidence) seen in the cardiac catheterization laboratory **(1)**. It is triggered by pain and anxiety, particularly in the setting of hypovolemia. Some elderly patients may exhibit all the findings of a vasovagal reaction without the hallmark finding of bradycardia **(66)**. In the study by Landau et al. **(67)**, more than 80% of such reactions occurred as vascular access was being obtained, with 16% occurring during sheath removal. This points to the importance of adequate preprocedure sedation and adequate administration of local anesthetic before catheter insertion is attempted. The treatment for vasovagal reaction consists of (a) cessation of the painful stimulus, (b) rapid volume administration (elevation of the legs on a linen pack and hand pumping of saline through the sidearm of the venous sheath), and (c) atropine (0.6 to 1 mg intravenously). If hypotension persists, additional pressor support (Levophed or Neosynephrine) may be needed. Although the vasovagal episode itself tends to be benign, patients with critical valvular heart disease may undergo severe and even irreversible decompensation if they are allowed to remain hypotensive from an indolently treated vasovagal reaction. When the vasovagal constellation occurs during catheter manipulation (instead of sheath insertion or removal), it should still be treated as outlined earlier, but the operator should be aware that vagal stimulation is one of the earliest findings in cardiac perforation (see later) when the pericardium is irritated by blood.

Conduction disturbances (bundle branch block or complete AV block) are an uncommon but potentially serious cause of bradycardia during cardiac catheterization **(68)**,**(69)**. They may be precipitated when the catheter impacts the area of the right bundle during right-sided heart catheterization. This may cause a transient change in complex on the monitor electrocardiogram (ECG) but requires no treatment except in the patient with preexisting left bundle branch block. In the case of right bundle branch block superimposed on preexisting left bundle branch block, asystole and cardiovascular collapse may ensue unless an adequate escape rhythm (i.e., a junctional escape) takes over. The same scenario may be seen when left bundle branch block is produced as the aortic valve is crossed in a patient with preexisting right bundle. Complete heart block may also be produced during use of rotational atherectomy, particularly in the right or circumflex coronary arteries (see Chapter 24); coronary thrombectomy in those vessels (or the grafts supplying them); or aortic valvuloplasty (see Chapter 26).

When complete heart block develops, atropine is rarely helpful in the setting of inadequate junctional escape and hemodynamic deterioration but should be given anyway, since it has few adverse effects. Coughing may help support the circulation and maintain consciousness while the right heart catheter is removed and a temporary pacing catheter is inserted. [We use the 7F balloon-tip Baim-Turi pacing catheter (USCI, Billerica, MA) for this purpose.] At one time, we placed such catheters prophylactically in patients with bundle branch block or planned right coronary intervention, but we abandoned this practice after retrospective review showed that frank asystole was rare and that there is generally time for insertion of a pacing catheter through the indwelling venous sheath **(70)**. The only procedures for which we place prophylactic right-sided pacing catheters now are balloon valvuloplasties and rotational atherectomy, particularly in the right and circumflex coronary arteries.

Perforation of the Heart or Great Vessels

Perforation of the cardiac chambers, coronary arteries, or intrathoracic great vessels is a rare event in diagnostic catheterization. In the cooperative study from 1968 **(2)**, 100 patients (0.8%) had perforation during diagnostic catheterization. Most involved the cardiac chambers, particularly the right atrium (33 cases), right ventricle (21 cases), left atrium (10 cases), and left ventricle (10 cases). Thirty of the 33 right atrial perforations involved transseptal catheterization, making the right ventricle the most common site for perforation in the remaining (nontransseptal) diagnostic procedures. The incidence of perforation is clearly related to the performance of procedures that use stiffer catheters (transseptal catheterization, endomyocardial biopsy, balloon valvuloplasty, needle pericardiocentesis, and placement of NIH or temporary pacing catheters). Elderly women (>65 years of age) seem particularly susceptible, since the walls of the right-sided heart chambers may be thinner. Higher-risk procedures involving stiff catheters should thus be performed only by individuals with greater catheterization experience who can exert all due care to avoid this problem.

When cardiac perforation does occur, it is usually heralded by bradycardia and hypotension due to vagal stimulation (see the preceding discussion of vasovagal reaction on p. 51) **(71)**. As blood accumulates in the pericardium, the cardiac silhouette may enlarge and the normal pulsation of the heart borders on fluoroscopy may become blunted. Hemodynamic findings of tamponade may develop in the form of arterial paradox and elevation of the right atrial pressure with loss of the *y* descent. If the patient is hemodynamically stable, a portable transthoracic echocardiogram may help document the presence of blood in the pericardial space. If hemodynamic compromise is severe or progressive, however, immediate pericardiocentesis should be performed via the subxyphoid approach. We use a disposable kit containing an 18-gauge needle, a J-tip guidewire, and a tapered catheter with multiple side holes, which is immediately available in the catheterization laboratory. We generally try to remove most of the free blood before reversing systemic heparinization with protamine, since early administration of protamine may cause blood in the pericardial space to “gel” and make aspiration impossible. Once pericardiocentesis has stabilized the situation and protamine has been administered, the operator must decide whether emergency surgery will be needed to oversew the site of perforation. This decision rests on the anatomic location of the perforation and the pace of ongoing bleeding (manifest as the rate of blood aspiration). Most perforations, in fact, will seal so that surgery is unnecessary. This is illustrated in an 18-year review from the Mayo Clinic **(72)**, during which time 92 patients (0.08% of invasive procedures) developed tamponade. This included 1.9% of valvuloplasties, 0.23% of electrophysiology studies, 0.08% of coronary angioplasties, and 0.006% of diagnostic catheterizations. The majority (57%) of patients were in frank hemodynamic collapse (systolic pressure < 60 mm Hg) at the time of pericardiocentesis. Echo-guided pericardiocentesis was successful in 91 cases, and was the only definitive therapy in 82% of cases (the remaining 18% requiring surgical intervention). There were no procedural deaths in this series, but there were three major complications (pneumothorax, intercostal artery injury, and right ventricular laceration), and seven patients (8%) died within 30 days of the procedure.

Perforation of the great vessels is extremely rare. The aorta is sufficiently elastic to resist perforation, except in the case of weakening by ascending aortic dissection or aneurysm. Aortic puncture may occur, however, during attempted transseptal puncture with too anterior a needle orientation (see Chapter 4). Rupture of the pulmonary artery is also rare, although care must be taken not to use stiff-tip guidewires in these thinner-walled vessels. Perforation of the branch pulmonary arteries has been reported when balloon flotation catheters are inflated while positioned in a distal branch (rather than in the left or right main pulmonary artery) **(73)**,**(74)**. Patients typically develop massive hemoptysis of bright red blood and require tamponade of the proximal pulmonary artery, embolization of the

bleeding branch, double-lumen endotracheal intubation to protect the noninjured lung, or even emergency lobectomy or pneumonectomy. Inflation of a balloon-tip catheter at the bedside should thus be performed only after a clear pulmonary artery trace is documented, in a slow, gradual fashion just until the shape of the waveform changes (i.e., from pulmonary artery to pulmonary capillary wedge). This is generally not an issue in the catheterization laboratory (where the position of the catheter tip can be confirmed fluoroscopically before it is inflated), but pulmonary artery rupture can still occur with lack of attention to balloon inflation combined with aggressive thrombolytic, antithrombotic, or antiplatelet therapy.

Perforation of a coronary artery was unheard of in the era of diagnostic catheterization and was a reportedly rare complication with conventional balloon coronary angioplasty **(75)**. With the advent of more aggressive new technologies for coronary intervention (in particular, directional atherectomy, rotational atherectomy, transluminal extraction atherectomy, and excimer laser angioplasty) the incidence of coronary perforation in these procedures has risen to 1% **(76)**. Many of these perforations, particularly those caused by distal positioning of a stiff or hydrophilic-coated guidewire, are limited to deep injury to the vessel wall with localized perivascular contrast staining. Free perforations may also occur, however, and the presence of systemic arterial driving pressure may lead to the development of frank tamponade within seconds to minutes (Fig. 3.2), particularly when the patient is well anticoagulated or has received a IIb/IIIa blocker **(77)**,**(78)**. The first countermeasure is to seal the site of leakage by inflation of a balloon catheter that spans the perforated segment. If a perfusion balloon catheter is used, antegrade flow to the myocardium can be maintained while the site of perforation is still effectively sealed. Pericardiocentesis may also be necessary if hemodynamic embarrassment is present. Many localized coronary perforations will seal with prolonged balloon inflation and reversal of heparinization by protamine. Other nonsurgical options include coil embolization if the bleeding site is in a small distal branch, or placement of a covered stent (see Chapter 25) to seal the perforation site in a larger proximal vessel. A free perforation with ongoing leakage is a strong indication for emergent surgical repair **(76)**.

FIG. 3.2.

Coronary perforation during directional atherectomy. **Left:** Eccentric stenosis of the mid-circumflex *(bold arrow)* just before small marginal branch *(small arrow).* **Left center:** Directional atherectomy device. **Right center:** Aneurysmal dilation of circumflex, indicating that atherectomy cuts had been made too distally (note location beyond small marginal branch). **Right:** Free leakage of contrast into the pericardial space, requiring use of a perfusion balloon to stop ongoing leakage, although pericardiocentesis and emergency bypass surgery were required.

Although they are extracardiac, dissection and perforation of vessels used as a route for advancing a cardiac catheter to the heart are also discussed in this section. Mediastinal and retropharyngeal hemorrhage has been reported as a complication of brachial left-sided heart catheterization in two patients, both of whom were excessively anticoagulated with warfarin (prothrombin times 42 and 23 seconds) and presented difficulty in catheter advancement from the brachiocephalic artery into the ascending aorta **(79)**. Supportive measures, including maintenance of the airway to avoid tracheal compression, normalization of clotting status, and blood replacement, were successful. Similar problems with the femoral approach have been reported with dissection or frank laceration of the iliac arteries. Iliac dissections produced with the guidewire may produce pain and may prompt switching to the contralateral femoral artery or the brachial approach but rarely progress to obstruction, since the direction of dissection is opposite that of antegrade blood flow. Cross-femoral access may then be used to dilate or stent the dissected iliac, if needed. In contrast, iliac *laceration* caused by a catheter or introducer sheath has the potential of causing brisk retroperitoneal bleeding. This is rarely controlled without surgical repair, although one instance has been reported in which a small leak was successfully sealed during occlusion by a 20-minute inflation of a peripheral angioplasty balloon **(47)**. When covered stents become available, they would also have the potential to repair iliac leaks from the percutaneous (rather than surgical) approach. The potential for iliac artery laceration underscores the need for careful wire and catheter advancement, and the benefits of performing all catheter exchanges over a guidewire at the level of the diaphragm, even if an arterial sheath is used.

Infections and Pyrogen Reactions

Since cardiac catheterization is an inherently sterile procedure, infection is extremely unusual. In fact, endocarditis

prophylaxis is not even recommended when cardiac catheterization is performed with usual sterile precautions **(80)**. Recommended technique includes shaving and cleaning the catheter introduction site with povidone-iodine [Betadine (Purdue Frederick, Norwalk, CT)], use of a nonporous drape, and adequate operator clothing (including a scrub suit, gown, and sterile gloves) **(81)**. Although antibiotics are not needed routinely, we still give a cephalosporin [Kefzol (Eli Lilly, Indianapolis, IN) 1 g on call and every 8 hours for 48 hours] whenever we perform a delayed intervention by exchanging sheaths that were placed in an earlier diagnostic procedure or when any break in sterile technique is suspected. When we must perform a repeat procedure within 2 weeks of an initial diagnostic procedure, we use the contralateral groin, since an increased infection rate has been reported with early reuse of the same groin site **(82)**. Special care should also be taken when performing catheterization through a femoral graft, since such grafts appear more prone to infection with potentially disastrous consequences **(83)**.

The most recent American College of Cardiology/American Heart Association task force does not insist that the operator perform a surgical scrub or wear a surgical cap and mask during femoral procedures **(57)**. These precautions are, however, recommended for catheterization by the brachial approach, where the risk of infection is ten times higher than the femoral approach (0.62% vs. 0.06%). Full sterile precautions (hand scrub, cap, and mask, including a splash shield) are also strongly recommended for the femoral approach when the procedure is prolonged, when the sheath will remain in place for any period, when a stent or permanent pacemaker is being implanted, or when a vascular graft is punctured. Those who have evolved to less stringent sterile precautions should be reminded that there have now been reports of life-threatening stent infections **(84)**, presumably seeded in the cardiac catheterization laboratory. Although some might accuse us of overkill, we have elected to use these precautions on *all* catheterization procedures in our laboratory, partially to protect the patient and partially to protect the operator from blood contamination, as recommended under the universal precaution guidelines of the Occupational Safety and Health Administration (OSHA).

Even with these precautions, exposure to blood through splashes, glove punctures, and needle sticks is one of the risks of working in the cardiac catheterization environment. Vaccination for hepatitis B is encouraged for all laboratory personnel, and anyone who suffers a puncture or laceration should report the event to the laboratory director and employee health personnel, who should give them the option to implement anti-HIV therapy. Retrospective analysis shows that prophylactic zidovudine (AZT) therapy may reduce the risk of infection after being stuck by a needle tainted with blood from an HIV-positive patient **(85)**.

To eliminate the risk of patient-to-patient contamination, we also avoid the multiuse drug vials and clean the room thoroughly between procedures.

With the preceding precautions, it is relatively unlikely that infection is the cause of a postprocedure fever. Although the patient should undergo the usual fever evaluation (chest x-ray, urinalysis, complete blood count, blood cultures), two other etiologies should be considered. Phlebitis may develop after brachial catheterization, with low-grade fever and a warm tender cord overlying the affected vein. Pyrogen reactions may present with shaking chills during or within the first hour after a catheterization, with a brief fever spike as high as 102°F. These reactions are caused by the presence of contaminating materials that may remain on incompletely cleaned catheter surfaces **(86)**. This was a common problem when cardiac catheters were washed and resterilized for repeat use in the 1970s, but has been virtually eliminated by the switch to disposable single-use commercial catheters that are certified as sterile and pyrogen-free. When a pyrogen reaction does occur, small doses of morphine (2 to 4 mg) seem to help alleviate the symptoms. Several countries, however, are now considering the resterilization and reuse of angioplasty balloon catheters as a cost-saving measure, again raising issues about residual ethylene oxide contamination from sterilization, the possibility of pyrogen reactions, and increased complications triggered by reduced performance of resterilized catheters. With progressive falls in the prices of new angioplasty balloons, the cost of reprocessing, medicolegal liability, and the dominant role played by the cost of (nonreusable!) stents, there has been little interest in pursuing reuse strategies for cardiac catheters in recent years.

Allergic and Anaphylactoid Reactions

Cardiac catheterization may precipitate allergic or anaphylactoid reactions to three materials: (a) local anesthetic, (b) iodinated contrast agent, or (c) protamine sulfate. True allergies to local anesthetic do occur but are more common with older ester agents (e.g., procaine) than with newer amide agents (lidocaine, bupivacaine) **(87)**. Some purported

allergic reactions to these agents are actually vasovagal episodes or reactions to preservatives. For patients who claim this history, however, use of preservative-free anesthetic (bupivacaine or mepivicaine) represents a practical alternative to performing the procedure without local anesthetic. Skin testing with the intended agent at 1:1,000 dilution can be performed before the procedure to verify absence of a reaction, if desired.

The most common allergic reactions (up to 1% of procedures) are triggered by iodinated contrast agents. In contrast to true anaphylactic reactions [which are mediated by immunoglobulin E (IgE)], reactions to contrast appear to involve degranulation of circulating basophils and tissue mast cells by direct complement activation (i.e., an anaphylactoid reaction) **(88)**. Release of histamine and other agents causes the clinical manifestations (sneezing, urticaria, angioedema of lips and eyelids, bronchospasm, or in extreme cases, shock with warm extremities due to profound systemic vasodilation). Risk of such reactions is increased in patients with other atopic disorders, allergy to penicillin, or allergy to seafood (which contains organic iodine) and may be as high as 15% to 35% in patients who have had a prior reaction to contrast. Premedication of patients with a seafood allergy or prior contrast reaction using the combination of prednisone [20 mg three times daily (tid) for 24 to 48 hours], an H1 antihistamine (diphenhydramine 25 mg tid), and an H2 blocker (cimetidine or ranitadine) can reduce the incidence of a second reaction to 5% to 10% and that of severe reactions (bronchospasm or shock) to below 1%. The recent availability of nonionic contrast agents (see Chapter 2), however, adds a further margin of safety, since the rate of severe cross-reactions in patients with prior reaction to an ionic contrast agent is also less than 1% **(89)**,**(90)**. For this indication, the true nonionic agents are preferable to an ionic low-osmolar agent such as Hexabrix to which cross-reactions may still occur. Although not absolutely necessary, use of a nonionic contrast agent can be combined with steroid and antihistamine premedication, if extra protection is desired for a patient with a severe prior reaction to contrast.

When a patient with a well-documented prior severe contrast reaction needs to undergo repeat catheterization, aortic pressure should be recorded before the catheter is cleared with contrast, since even this small amount of contrast can cause significant histamine release. The “money shots” of the coronaries should be obtained first, since a severe contrast reaction to the left ventriculogram may preclude further angiography. If a severe reaction occurs, it can be reversed with an intravenous injection of dilute epinephrine **(91)**: One mL of 1:10,000 epinephrine (i.e., 0.1 mg of epinephrine per milliliter) is drawn up from the syringe on the crash cart, diluted further to a total volume of 10 mL (10 mg/mL), and labeled so that it is not mistaken for flush. The epinephrine is administered into the right-sided heart catheter in boluses of 1 mL (or 10 μg) every minute, until arterial pressure is restored. It is rare to have to give more than 10 mL (100 μg) in total, and excessive doses should be avoided, since they may precipitate life-threatening hypertension, tachycardia, or even ventricular fibrillation.

Although reactions to contrast are the most common allergic reaction in the cardiac catheterization laboratory, reactions to protamine sulfate, a biologic product derived from salmon eggs, can also occur. These reactions seem to be more common in insulin-dependent diabetics, who have received NPH insulin (which contains protamine) **(92)**. Although this observation has not been confirmed in another study **(93)**, we tend to omit heparin for diagnostic procedures in such patients, or allow it to wear off before sheath removal rather than take a chance by administering protamine. If a severe anaphylactic reaction occurs, it can be treated as outlined earlier. When giving protamine, administer it slowly (over 5 minutes), since more rapid administration can provoke severe back pain of unknown etiology.

Another allergic reaction that should be considered-even though it is rarely seen in the cardiac catheterization laboratory itself-is heparin-induced thrombocytopenia (HIT) **(94)**. This is defined as a fall in platelet count by at least 50% when accompanied by a positive serologic test for the responsible (usually IgG) antibody. This antibody binds to platelet factor 4 and the PF-4/antibody complex binds to the platelet Fc receptor to cause platelet activation. It seems to be more common with bovine-derived than with porcine-derived heparin. Although onset is typically 7 to 10 days, earlier onset (as early as the first or second day) may be seen in previously sensitized patients. This requires that further heparin administration be curtailed and that any indications for ongoing anticoagulation [including the Heparin-Induced Thrombocytopenia and Thrombosis (HITT) syndrome of aggressive arterial and venous thrombosis] be addressed using an alternative anticoagulant. Options include one of the low-molecular-weight heparin preparations **(95)**, although they frequently cross-react with heparin antibodies, the heparinoid (Organan, danaproid) **(96)**, or one of the direct antithrombin compounds (hirudin, hirulog, or argatroban) **(97)**. Obviously, the same considerations apply if a patient with a history of HIT requires a repeat interventional procedure. If thrombocytopenia develops after a coronary interventional procedure, the assay for heparin antibodies is particularly important, since thrombocytopenia has also been reported in 3.9% of patients within 2 to 12 hours after being treated

with the IIb/IIIa receptor blocker abciximab (ReoPro, Eli Lilly, Indianapolis, IN) **(98)**. In 0.9%, severe thrombocytopenia (platelet counts < 50,000) develops. Other potent IIb/IIIa receptor blockers have also been associated with approximately 1% incidence of thrombocytopenia.

Renal Dysfunction

Temporary or permanent renal dysfunction is a serious potential complication of cardiac angiography. The precise mechanism of contrast-induced renal dysfunction (vasomotor instability, increased glomerular permeability to protein, direct tubular injury, or tubular obstruction) has not been established, but at least 5% of patients experience a transient rise in serum creatinine greater than 1 mg/dL following cardiac angiography **(99)**. Patients with diabetes, multiple myeloma, volume depletion, or preexisting renal dysfunction, or who are receiving certain drugs [e.g., gentamycin, angiotensin-converting enzyme inhibitors, nonsteroidal antiinflammatory agents (NSAIDS)] are at increased risk (up to 50%) of this complication. Most such elevations in creatinine are nonoliguric, peak within 1 to 2 days, and then return to baseline by 7 days. Fewer than 1% of patients who develop contrast-induced renal dysfunction go on to require chronic dialysis. Although animal data suggest that low-osmolar contrast agents may have lower renal toxicity, prospective trials comparing high- and low-osmolar contrast agents have failed to show consistent benefit **(100)**,**(101)**. In our laboratory, however, we use the smallest possible volumes of low-osmolar agents and aggressive prehydration (see later) when studying patients with a baseline serum creatinine of more than 2.5 mg/dL.

The main defense against contrast-induced nephropathy is limitation of total contrast volume to 3 mL/kg (or 5 mL/kg divided by serum creatinine, in patients with elevated baseline creatinine). In the 1990 SCA&I registry, the mean volume of contrast administered during diagnostic cardiac catheterization was 130 mL for diagnostic procedures and 191 mL for angioplasty procedures, indicating that staying within 3 mL/kg limit for patients with normal renal function **(6)** usually is possible. In patients with reduced renal function, extra attention must be paid to limiting unnecessary angiographic views and multiple contrast “puffs” during interventional wire and device placement, which may drive up the total contrast volume. Adequate prehydration is also critically important in any patient with impaired baseline renal function. In a classic study **(102)**, 26% of patients with a mean baseline serum creatinine of 2.1 mL/dL had a rise in serum creatinine of more than 0.5 mg/dL. Hydration with half the normal saline for 12 hours before and after the contrast procedure provided the best protection against creatinine rise (which then occurred in 11%, as compared with 26% to 28% of patients who received hydration in combination with either furosemide or mannitol). In a more recent single-center study **(103)**, 98 patients with a baseline creatinine of more than 1.8 mg/dL (mean 2.5 mg/dL) who received a mean of 160 mL of contrast had a mean change in creatinine of 0.6 mg/dL, but 15% developed a peak creatinine of more than 5 mg/dL at 48 hours and 7% went on to dialysis. If postprocedure hourly urinary flow rate could be maintained at a rate of more than 150 mL/hr by the use of fluid loading, low-dose dopamine, and furosemide (as needed), the incidence of severe renal failure (peak creatinine of more than 5 mg/dL at 48 hours, or dialysis) was reduced by half (from 19.7% to 8.1%). Another cause of renal failure following cardiac catheterization is systemic cholesterol embolization **(104)**,**(105)**. This syndrome is diagnosed clinically in roughly 0.15% of catheterizations, although cholesterol emboli can be identified pathologically in a far greater number of patients. Patients at greatest risk are those with diffuse atherosclerosis, in whom insertion of a guiding catheter will frequently produce a shower of glistening particles on the table drape. The hallmarks of cholesterol embolization are evidence of peripheral embolization (including livido reticularis, abdominal or foot pain, and purple toes). Episodic hypertension or systemic eosinophilia may be apparent well before the other manifestations develop. Renal failure due to cholesterol embolization tends to develop slowly (over weeks to months, rather than over 1 to 2 days as is seen with contrast nephropathy). Half of the patients with this syndrome progress to frank renal failure. Renal biopsy can confirm the presence of cholesterol clefts but is seldom necessary for diagnosis. Treatment is purely supportive.

Other Complications

Hypotension

Reduction in arterial blood pressure is one of the most common problems seen during catheterization. This reduction represents the final common manifestation of a variety of conditions including: (a) *hypovolemia,* due to inadequate prehydration, blood loss, or excessive contrast-induced diuresis; (b) *reduction in cardiac output,* due to ischemia, tamponade, arrhythmia, or valvular regurgitation; or (c) *inappropriate systemic arteriolar vasodilation,* due to

vasovagal, excessive nitrate administration, or vasodilator response to contrast or mixed inotrope-vasodilator drugs such as dopamine or dobutamine. Few places, however, are as well equipped as the cardiac catheterization laboratory, to recognize, diagnose, and treat hypotension. We perform right-sided heart catheterization in only selected diagnostic procedures but in most interventional procedures (where we prefer to leave the right-sided heart catheter in the pulmonary artery for the duration of the case). If routine right heart catheterization is not done, evolving hypotension is certainly an adequate reason to insert such a catheter.

Low filling pressures mandate rapid volume administration through the peripheral intravenous line and the sidearm of the venous sheath (500 to 1,000 mL of normal saline can be given in 5 minutes by this route) and consideration of potential sites of blood loss (expanding thigh hematoma, retroperitoneal bleeding). If low filling pressures are combined with inappropriate bradycardia, atropine should be given for a potential vasovagal reaction. High filling pressures, however, suggest primary cardiac dysfunction and should prompt consideration of ischemia, tamponade, or sudden onset of valvular regurgitation. Such patients should be supported empirically by inotropic agents (dopamine, dobutamine, milrinone), vasopressors (levophed or neosynephrine), or circulatory support devices [intraaortic balloon counterpulsation, cardiopulmonary support (CPS)] while a more precise etiology is uncovered and treated. The operator also must decide whether the precipitating problem will require surgical intervention, and whether that intervention should be performed immediately after an initial attempt at stabilization in the cardiac catheterization laboratory. If bradycardia is present and does not respond to atropine, consideration should be given to atrial (or AV) sequential pacing to preserve the atrial kick in such patients. One of the most common oversights in managing hypotension, is the failure to assess the cardiac output through thermodilution or measurement of pulmonary arterial oxygen saturation. On several occasions, high pulmonary arterial saturation in a hypotensive patient has signaled coexistent sepsis, contrast reaction, or an idiosyncratic vasodilator reaction to dopamine infusion.

The essential importance of initial empirical and then definitive correction of hypotension and its causes-before hypotension leads to secondary ischemia and an irreversible spiral of left ventricular dysfunction-cannot be overemphasized in providing salvage treatment for patients who might otherwise go on to have major complications.

Volume Overload

Patients in the cardiac catheterization are prone to volume overload due to the administration of hypertonic contrast agents, myocardial depression, or ischemia induced by contrast, poor baseline left ventricular function, as well as their supine position and attempts to volume-load patients at risk for contrast-induced renal dysfunction. The best treatments are prevention by optimizing volume status before or early in the procedure and by use of low-osmolar contrast agents. The support measures described earlier (inotropes, diuretics, vasodilators, balloon pumping) should also be applied in a progressive manner before the patient goes into frank pulmonary edema with the resultant agitation and desaturation. Once pulmonary edema develops, even more aggressive treatment is warranted. Allowing the patient to sit up partially while morphine and nitroprusside are administered to bring filling pressures down may be necessary. If respiratory failure seems imminent, anesthesia support should be requested early enough to allow intubation before a full arrest develops.

Anxiety/Pain

Cardiac catheterization procedures should be well tolerated with oral sedative pretreatment [diazepam (Valium) 5 to 10 mg, and diphenhydramine (Benadryl) 25 to 50 mg] and liberal use of local anesthetic at the catheter insertion site. However, patients' amount of discomfort, level of anxiety, and tolerance for either vary widely. The first effort should be to understand why the patient is having pain (vascular complication, perforation, coronary occlusion, ischemia) and whether anything can be done to reverse the problem. In the meantime, the catecholamine surge associated with pain and anxiety may worsen the condition of a patient who came to the cardiac catheterization laboratory with unstable angina, aortic stenosis, congestive heart failure, or hypertrophic myopathy. It is common practice in our laboratory, therefore, also to manage such complaints symptomatically with small intravenous doses of morphine (2 to 4 mg), fentanyl (25 to 50 mg), and midazolam (Versed, Roche Laboratories, Nutley, NJ; 0.5 to 1 mg). This policy makes the procedure more tolerable for both the patient and the staff, as long as care is taken not to oversedate the patient or overlook an important and treatable etiology for patient complaints. Guidelines for monitoring conscious sedation require monitoring of blood pressure, respiratory rate, and pulse oximetry for 30 minutes after such medications are administered. The antagonist drugs-naloxone (Narcan) for opiates and flumazenil (Mazicon) for benzodiazepines-should also be stocked wherever the agonist drugs are used for conscious sedation.

Respiratory Insufficiency

Problems with adequate ventilation or oxygenation are not uncommon in a cardiac catheterization that deals predominantly with unstable patients. This may result from pulmonary edema, baseline lung disease, allergic reaction, or oversedation. As a screening measure, we routinely send the first arterial sample after sheath insertion to the blood gas laboratory for measurement of pH, PCO2, as well as PO2. Patients are then monitored throughout the procedure with a finger pulse oximeter to detect progressive desaturation. Data from such monitoring show that low-flow supplemental oxygen (2 L/min via nasal prongs) helps avoid episodes of desaturation (saturation < 90%) that otherwise occur with surprising frequency during cardiac catheterization (34%) or coronary angioplasty (56%) **(106)**. If oxygen consumption is to be measured as part of a calculation of cardiac output by the Fick method, however, supplemental oxygen administration should not be begun until after that measurement (or should be interrupted for a least 10 minutes before the oxygen consumption is measured).

Retained Equipment

Although diagnostic and therapeutic cardiac catheters have a high degree of reliability, failures can and do occur whereby devices knot **(107)**, become entrapped **(108)**, or leave fragments in the circulation **(109)**,**(110)**. Most of these events are precipitated when such devices are stressed beyond their design parameters (e.g., when a coronary angioplasty guidewire is rotated multiple times in a single direction while its tip is entrapped in a total occlusion, or when a bare-mounted coronary stent cannot be advanced across a lesion and strips off the delivery balloon during attempted withdrawal). Operators should thus be familiar with device performance limits and avoid placing devices into situations that promote failure. Operators should also be familiar with the use of vascular snares, bioptomes, baskets, and other devices and techniques that can be used to recover the errant fragments **(111)** when devices do fail.

OTHER IMPORTANT ASPECTS OF PROCEDURAL COMPLICATION

Caseload

Although many complications are unavoidable, several studies have demonstrated a clear inverse correlation between the caseload of a cardiac catheterization laboratory and each operator, and their incidence of major complications. For coronary angiography, the mortality rate in institutions performing fewer than 100 diagnostic procedures per year was eight times higher than that in institutions performing more than 400 procedures per year. These data were interpreted to mean that greater caseload leads to greater skill and technical proficiency and fewer complications, and are reflected in the most recent ACC/AHA Guidelines **(57)**, which support a minimum of 300 cases per year for an adult catheterization laboratory and a minimum of 150 cases per physician each year. Lower annual caseloads may be permitted for physicians who have demonstrated skills or who limit themselves to lower-risk patient populations. One study of eight cardiac catheterization laboratories in the state of Washington thus had an extremely low rate of major complications in association with coronary angiography, even though the caseload per laboratory (average 50 to 250 cases per year) and caseload per angiographer (average 65 cases per year) were low **(112)**.

For coronary intervention, several studies have shown a similar relationship between higher institutional and operator volumes, and lower rates of major complications. Medicare data regarding coronary angioplasty thus show that institutions performing fewer than 200 such procedures per year, and operators performing fewer than 75 interventions per year, have more than twice the mortality and emergency surgery rates of higher-volume institutions **(113)**. Ellis et al. **(114)** reported similar findings in high-volume institutions, and Kastrati et al., have shown this pattern persisting even in the era of stenting **(115)**. These data support the recommendations made by the American College of Cardiology regarding maintaining proficiency in interventional procedures **(116)**. The data seem relatively clear: “Practice makes perfect” for both the institution and the individual operator performing invasive cardiac procedures.

Speed

The speed with which a catheterization procedure is accomplished is also widely regarded as one factor that determines the risk of complication. Unfortunately, few data are available on this subject. The Cooperative Study, which analyzed the duration of diagnostic cardiac catheterization procedures in 16 participating laboratories in the late 1960s **(2)**, found that there was a bell-shaped curve, with the most common duration being 2.0 to 3.0 hours (5,022 cases, 41% of total procedures; median, 2.5 hours), with 4,207 procedures (34%) lasting 1.0 to 2.0 hours and 2,054 procedures (17%) lasting between 3 and 4 hours. It was rare for a procedure to last less than 1 hour (1.9%) or longer than 5 hours (2.8%).

Data compiled in our laboratory in the early 1990s show that the average time required (from the administration of xylocaine to that of protamine, using the femoral approach) for a procedure-including right-sided and left-sided heart catheterization, left ventricular angiography, and coronary angiography-is 45 to 60 minutes. This shorter time has been accomplished despite the need for angiography of saphenous vein and internal mammary grafts in the substantial fraction of the diagnostic catheterization population who have now undergone prior coronary bypass surgery. This shorter time also is consistent with the average arterial times of 33 minutes for diagnostic procedures in the 1990 SCA&I registry **(6)**. Even for procedures involving coronary intervention, the average procedure time is only 70 to 90 minutes, consistent with the 68-minute arterial time for interventional procedures in the 1990 SCA&I registry.

Whereas shorter procedure times have correlated with decreased overall risk, slow speed of performing a procedure does not necessarily carry an increased risk of a complication, unless the slow speed reflects lack of operator skill. Instead, many longer cardiac catheterization procedures are the consequence of factors that themselves tend to be associated with a high risk of complication. For example, the elderly patient with extensive atherosclerosis and arterial tortuosity may have a long procedure because of technical difficulties associated with catheter passage. Patients who frequently have more extensive disease and diminished reserve may also have an increased risk of complications. In this instance, the high risk is not necessarily caused by the increased duration of the procedure: The two are “true, true; unrelated.” Similarly, a young patient with normal vessels and minimal cardiac disease may have a rapid catheterization procedure, but speed of the procedure in this instance cannot fairly be credited with the observed low risk. Thus duration of the procedure should be considered as an important “independent” risk factor, only when it can clearly be related to lack of skill or experience on the part of the operator, or when it leads to severe cardiac decompensation in a critically ill patient poorly prepared to spend more than the minimal time in the supine position.

Pseudocomplications

Finally, a word relevant to “pseudocomplications” of cardiac catheterization is in order. Patients suffering from serious cardiac disease experience major cardiac events (myocardial infarction, ventricular arrhythmia, systemic embolus) as part of the natural history of their disease. If one of these events happens to occur during or within 24 hours after a cardiac catheterization, is it fair to regard it always as a complication of the procedure? Hildner and coworkers examined events that occurred from 24 hours before to 72 hours after scheduled catheterizations **(117)**,**(118)**. The incidence of pseudocomplications or events occurring in the 24 hours before scheduled catheterization was 0.81%, including 0.24% deaths. The same period after catheterization saw a 0.81% incidence of catheterization procedure-related complications with no deaths. It is thus clear that the incidence of complications after cardiac catheterization also includes the occurrence of some unexpected major cardiac events that are driven by natural history of the patient's underlying cardiac disease.

Although it is unlikely that anything we do in the catheterization laboratory will completely eliminate these disease-related problems, we each have an obligation to understand how each of the true procedure-related complications described here arises, how to avoid it whenever possible, how to recognize it when it occurs, and how to treat it appropriately to mitigate as much as possible any long-term sequelae. To achieve this goal requires close tracking by the lab director, periodic public review of complication data (as well as timely evaluation of clusters of unusual problems), and ongoing refinement of the laboratory policies and procedures coupled with continuing staff education regarding those policies.