Right-Sided Heart Catheterization

Flow-directed pulmonary artery catheters, also called Swan-Ganz catheters after inventors Jeremy Swan and William Ganz, were initially used to guide therapy after acute myocardial infarction, but are now used in a variety of settings. There is, however, no universally accepted indication for their use, because right-sided heart (pulmonary artery [PA]) catheterization has not been shown to improve outcome.

Indications and Contraindications

PA catheterization is useful in a number of diagnostic applications. It has been used in the differentiation of various causes of shock and pulmonary edema; the evaluation of pulmonary hypertension; the differentiation of pericardial tamponade from constrictive pericarditis and restrictive cardiomyopathy; the diagnosis of left-to-right intracardiac shunts; and to guide fluid management and hemodynamic monitoring of patients after surgery or complicated myocardial infarction and for patients in shock, heart failure, etc.

Although there is no absolute contraindication for use of PA catheters, care should be taken in patients with severe pulmonary hypertension and in the elderly. Fluoroscopic guidance is recommended in patients with preexisting left bundle-branch block, because it likely reduces the risk of right bundle-branch damage during catheter insertion and consequent complete heart block.

PA (Swan-Ganz) Catheter: Insertion Technique

The PA catheter can be inserted via the internal jugular vein, subclavian vein, antecubital vein, or femoral vein. After the site is prepped and draped, local anesthesia is administered to the site with 5 to 10 mL of 2% lidocaine by use of a 25-gauge needle. The vein is entered with a needle, preferably by micropuncture and preferably under ultrasound guidance (especially for the internal jugular vein), and an introducer needle. The vein is entered with a needle, preferably by micropuncture and preferably under ultrasound guidance (especially for the internal jugular vein), and an introducer catheter is inserted by use of a standard technique. Under sterile conditions, the PA catheter should be removed from the packaging and the proximal and distal ports flushed with heparinized saline to ensure an air-free system; stopcocks should be placed on the end of the ports. The balloon inflation syringe should be filled with 1.5 mL of air and the balloon inflated under saline to ensure there are no air leaks in the balloon. The pressure monitoring system should be prepared for use according to institutional practice to ensure an air-free system.

The PA catheter can be inserted either under fluoroscopic guidance (preferred) or under the guidance of the pressure waveforms. Fluoroscopic guidance is recommended in patients with a markedly enlarged right atrium or ventricle or severe tricuspid regurgitation or in those with left bundle-branch block. The catheter should be advanced to the vena cava/right atrium junction (10–15 cm from the internal jugular vein or 25–30 cm from the femoral vein) and the balloon inflated. The catheter is designed to be flow-directed and will aid the flow of the catheter along the direction of blood flow (right atrium to PA). Pressure measurements and sampling of blood for measurement of oxygen saturation can be performed as the catheter is advanced through the various chambers of the heart, although it is sometimes easier to advance distally to the PA and make measurements on the way back out (that is, if the PA catheter is not meant to stay in place). The sequential changes in the pressure waveform are as shown in Figure 1. Once a pulmonary capillary wedge pressure tracing is seen, the balloon should be deflated and the catheter pulled back by 1 to 2 cm to remove any redundant length or loop in the right atrium or ventricle. The tip should be maintained in a position where full or near-full inflation volume is necessary to produce a wedge tracing. The ideal position of the catheter is the zone 3 region of the lung (lower zone). For subsequent wedge tracings, the balloon should be inflated with the minimum amount of air to produce a wedge tracing. Excess can cause overwedging, in which the pulmonary capillary wedge pressure will be higher because of transmittal of pressure from the balloon and with loss of characteristic waveforms. For precautions, please refer to the accompanying slide set in the online-only Data Supplement.
Pressure Recordings
Pressure should always be recorded at end expiration (except in patients on positive end-expiratory pressure), as under normal conditions, pressures will be lower in inspiration because of the decrease in intrathoracic pressure. Before any pressure measurements are taken, it is imperative to perform zeroing and referencing of the system. Zeroing is accomplished by opening the system to air so as to equilibrate with atmospheric pressure and referencing by ensuring that the air-fluid interface of the transducer is at the level of the patient’s heart (phlebostatic axis; fourth intercostal space midway between anterior and posterior chest wall). It is imperative to ensure that the transducer is at the level of the heart, because for every inch the heart is offset from the reference point of the transducer, a 2-mm Hg degree of error will be introduced. If the heart is lower than the transducer, the pressure will be erroneously low, and if the heart is higher, the pressure will be erroneously high. The dynamic response of the pressure monitoring system should be determined by measuring the resonant frequency and the damping coefficient of the system by use of the fast-flush test, as described in Figure 2. Pressure wave interpretations and differential for the common wave patterns from the right atrial and pulmonary capillary wedge pressure tracings are shown in Table 1.

Cardiac Output Measurement
Three indirect methods for cardiac output determinations are (1) the dye indicator dilution technique, (2) the Fick technique, and (3) the thermodilution technique. The Fick and thermodilution techniques are the most widely used, and the former is considered the gold standard for cardiac output measurement.

The Fick principle is based on the observation that the total uptake of (or release of) oxygen by the peripheral tissues is equal to the product of the blood flow to the peripheral tissues and the arterial-venous concentration difference (gradient) of oxygen. It is therefore based on measurement of the ratio of oxygen consumption to oxygen extraction. Oxygen consumption can be measured with an oxygen hood or estimated to be 250 mL/min or 125 mL/min per square meter of body surface area under resting conditions. Oxygen extraction is measured as the arteriovenous oxygen difference, which is given by the following formula: 13.4×hemoglobin concentration×(SaO₂−SvO₂). SaO₂ is the arterial oxygen saturation, whereas SvO₂ is the mixed venous oxygen saturation, measured as (3×superior vena cava saturation+inferior vena cava saturation)/4. This is most accurate in low-output states and is considered the “gold standard.”

In the thermodilution technique, a known amount of solution (usually saline) is injected into the proximal port (right atrium), where it mixes and cools the blood, which is recorded by a thermistor located at the distal end of the catheter. Cardiac output is inversely proportional to the area under the curve. The thermodilution technique is not reliable in patients with severe tricuspid or pulmonic valve regurgitation, because it results in lower peak and a prolonged washout phase due to recirculation that results in underestimation of cardiac output. It is also not reliable in patients with intracardiac shunts (it overestimates cardiac output).

Derived Parameters
PA catheter measurements can also be used to calculate systemic and pulmonary vascular resistance, stroke work index, shunt fraction, and valve area (Table 2). However, the vascular resistance obtained is the least accurate (of the measures obtained from the catheter) and the most sensitive...
to minor inaccuracies in data acquisition. Hemodynamic parameters that help differentiate constrictive pericarditis from restrictive cardiomyopathy are outlined in Table 3.

**Coronary Angiography**

Coronary artery disease is the leading cause of death for both men and women in the United States. More than 1.5 million cardiac catheterizations are performed every year in the United States, primarily to diagnose coronary artery disease. The indications for diagnostic coronary angiography are listed in the accompanying slide sets, and more detailed information can be obtained from the American College of Cardiology/American Heart Association guidelines.3

Although there are no absolute contraindications to cardiac catheterization, relative contraindications include coagulopathy, such as patients taking warfarin or after thrombolytic therapy (a radial approach can be attempted based on urgency); decompensated congestive heart failure; uncontrolled hypertension; pregnancy; inability of the patient to cooperate; active infection; renal failure; and contrast medium allergy.

**Coronary Angiography: Technique**

After a thorough history has been obtained, a thorough physical examination has been performed, and written informed consent has been obtained from the patient, conscious sedation with a narcotic and a benzodiazepine should be used before vascular access is attempted. Vascular access can be either femoral (described by Bangalore and Bhatt3a in the section on vascular access and closure devices), radial, or brachial. The selected diagnostic catheter should be flushed with saline to ensure an air-free system. Once arterial access is obtained (as described in the section on vascular access and closure devices), a catheter of appropriate size and configuration is obtained (as described in the section on vascular access and closure devices), radial, or brachial. The selected diagnostic catheter should be flushed with saline to ensure an air-free system. Once arterial access is obtained (as described in the section on vascular access and closure devices), a catheter of appropriate size and configuration is advanced over a 0.035- or 0.038-inch guidewire. Once it is in the ascending aorta, the guidewire is removed, and the catheter is allowed to bleed back to remove any thrombus or atherosclerotic debris. The catheter is then connected to a manifold assembly connected to a pressure transducer for continuous central pressure monitoring and is flushed to ensure an air-free system.

Before any pressure is measured, zeroing and referencing must be performed. The transducer should be opened to air to zero out the system. Care must be taken to ensure that the pressure transducer is at the level of the phlebostatic axis, which is roughly the midportion between the anterior and posterior chest wall along the left fourth intercostal space. The central aortic pressure should be recorded and compared with the cuff measured brachial pressure. If there is a considerable difference between the 2, subclavian artery stenosis should be in the differential. The catheter should then be filled with 3 to 4 mL of contrast and advanced to engage

<table>
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<tr>
<th>Table 1. Pressure Wave Interpretation</th>
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<tr>
<td>Wave Pattern</td>
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<tr>
<td>Cannon ‘a’ wave</td>
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<tr>
<td>Tall ‘a’ wave</td>
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<tr>
<td>No ‘a’ wave</td>
</tr>
<tr>
<td>Tall ‘v’ wave</td>
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<tr>
<td>Loss of ‘y’ descent</td>
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<td>Exaggerated ‘y’ descent</td>
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AV indicates atrioventricular; AVNRT, atrioventricular nodal reentry tachycardia; and VSD, ventricular septal defect.

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<th>Table 2. Derived Parameters Using a Pulmonary Artery Catheter</th>
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<tr>
<td>Parameter</td>
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<td>Systemic vascular resistance</td>
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<td>Pulmonary vascular resistance</td>
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<td>Stroke work index</td>
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<td>Shunt fraction</td>
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<td>Mitral valve area</td>
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<td>Aortic valve area</td>
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<td>Aortic valve area (Hakki equation)</td>
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</table>

MAP indicates mean arterial pressure; RAP, right atrial pressure; CO, cardiac output; MPAP, mean pulmonary artery pressure; PCWP, pulmonary capillary wedge pressure; LVEDP, left ventricular end-diastolic pressure; SVI, stroke volume index; LV, left ventricle; RV, right ventricle; SaO\(_2\), oxygen saturation, arterial; MVO\(_2\), oxygen saturation, mixed venous; PV\(_O_2\), oxygen saturation, pulmonary veins; PaO\(_2\), oxygen saturation, pulmonary artery; DFP, diastolic filling period; HR, heart rate; SEP, systolic ejection period; and \(\Delta P\), mean pressure gradient. Please note for the Hakki equation, peak-to-peak gradient can be used instead of the mean systolic gradient.

<table>
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<tr>
<th>Table 3. Hemodynamic Parameters That Help Differentiate Constrictive Pericarditis From Restrictive Cardiomyopathy</th>
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<tbody>
<tr>
<td>Parameter</td>
</tr>
<tr>
<td>LVEDP-RVEDP, mm Hg</td>
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<tr>
<td>RV systolic, mm Hg</td>
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<tr>
<td>RVSP/RVSP, mm Hg</td>
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<tr>
<td>RV/LV interdependence</td>
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<tr>
<td>RV/LV pressure waveform (square root sign)</td>
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<td>RA pressure waveform (square root sign)</td>
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</table>

LVEDP indicates left ventricular end-diastolic pressure; RVEDP, right ventricular end-diastolic pressure; RV, right ventricle; RVSP, right ventricular systolic pressure; LV, left ventricular; RA, right atrial; and PCWP, pulmonary capillary wedge pressure.
the coronary ostium, in the left anterior oblique (LAO) projection. After ensuring that there is no ventricularization or damping of the pressure, 2 to 3 mL of contrast should be injected to confirm the position of the catheter in the coronary ostium. Coronary angiography should be performed in standard views in orthogonal planes to visualize the lesion and serve as a roadmap for percutaneous coronary intervention (PCI). Nonstandard views should be considered on the basis of the lesion location, orientation of the heart, and patient body habitus. Before contrast is injected, with every view, care should be taken to ensure there is no ventricularization or damping of the pressure waveforms.

Complications
The overall risk of major complications with coronary angiography is 1% to 2%. This includes death, myocardial infarction, stroke, bleeding, vascular complications, and contrast reactions.

Catheter Selection
Selecting the right catheter is important, and the choice depends on the following:

1. Access site: Choice of catheters depends to a certain degree on the access site (femoral versus radial versus brachial).
2. Aortic width: Normal aortic width is 3.5 to 4.0 mm, narrow is <3.5 mm, and dilated is >4.0 mm.
3. Coronary ostial location: High versus low; anterior versus posterior.
4. Coronary ostial orientation: Superior, inferior, horizontal, or shepherd’s crook (for right coronary artery only).

It is preferable to use standard workhorse catheters for routine coronary angiography, such as the Judkins right size 4 (JR4) and Judkins left size 4 (JL4). It is important to always ensure coaxial alignment of the catheter. Catheters have 2 main curves: A primary (distal) curve and a secondary (proximal) curve. The distance between the 2 curves denotes the length of the catheter. As a general rule, shorter-curve catheters are better suited for superior ostial takeoffs, whereas the longer-curve catheters are better suited for inferior ostial takeoffs.

Standard Angiographic Views
The standard angiographic views for the left and right coronary arteries are detailed in the slide set. For the left coronary artery, many operators follow a standard order of views, such as starting with the right anterior oblique (RAO) caudal (RAO 20°, caudal 20°), PA cranial (PA 0°, cranial 30°), shallow RAO cranial (RAO 10°, cranial 40°), LAO cranial (LAO 50°, cranial 30°), LAO caudal (LAO 50°, caudal 30°), and PA caudal (PA 0°, caudal 30°) for the left coronary system. For the right coronary artery, LAO 30°, RAO 30°, and PA cranial (PA 0°, cranial 30°) are frequently used. Nonstandard views are used if the standard views are not clear and if additional information about a lesion is needed.

Systematic Interpretation of Coronary Angiography
A systematic interpretation of a coronary angiogram would involve evaluation of the extent and severity of coronary calcification and lesion quantification in at least 2 orthogonal views assessing for severity, calcification, presence of ulceration/thrombus, degree of tortuosity, American College of Cardiology/American Heart Association lesion classification, and reference vessel size. In addition, grading of the TIMI (Thrombolysis In Myocardial Infarction) flow and that of the TIMI myocardial perfusion blush grade should be performed. Also, it is important to identify and quantify the coronary collaterals. Some of the definitions are included in Table 4.

Percutaneous Coronary Intervention
It is estimated that more than 1.2 million PCI procedures are performed every year in the United States. The indications for PCI are listed in the accompanying slide sets, and more detailed information can be obtained from the American College of Cardiology/American Heart Association guidelines on percutaneous coronary intervention and the appropriateness criteria. The contraindications and cautions are similar to those described under coronary angiography.

PCI Technique
After the clinician has ensured that the patient understands the procedure and has provided informed consent, conscious sedation is administered with a narcotic and a benzodiazepine. As described under the section on coronary angiography, vascular access can be femoral, radial, or brachial. Antiplatelet therapy with aspirin should be given before the procedure, and a loading dose of thienopyridine (clopidogrel or prasugrel) should be given periprocedurally. Antithrombotic therapy with unfractionated heparin, low-molecular-weight heparin, or bivalirudin should be given and the activated clotting time maintained at 250 to 300 seconds (for unfractionated heparin given as monotherapy). Glycoprotein receptor IIb/IIIa inhibitors can also be used based on the procedure. The selected guiding catheter (connected to a Y-port) should be flushed with saline to ensure an air-free system.

Once arterial access is obtained (as described by Bangalore and Bhatt in the section on vascular access and closure devices), a guiding catheter of appropriate size and configuration is advanced over a 0.035- or 0.038-inch guidewire. Once in the ascending aorta, the guidewire is removed, and the catheter is allowed to bleed back to remove any thrombus or atherosclerotic debris. The catheter is then connected to a manifold assembly that is connected to a pressure transducer for continuous central pressure monitoring. The guiding catheter is flushed to ensure an air-free system and should then be filled with 3 to 4 mL of contrast and advanced to engage the coronary ostium, in the LAO 30° projection. After ensuring that there is no ventricularization or damping of the pressure, 2 to 3 mL of contrast should be injected to confirm the position of the catheter in the coronary ostium.

After adequate antithrombotic agents have been given, a 0.014-inch guidewire with a curve placed at its tip is advanced through the guide catheter into the coronary artery and across the lesion. At this stage, in the setting of thrombotic ST-elevation myocardial infarction lesions, a
manual aspiration catheter can be used to aspirate thrombus. For saphenous vein graft interventions, an embolic protection device should be deployed before any angioplasty or stenting (if feasible, as described in the upcoming article and section by Bangalore and Bhatt on embolic protection devices). An appropriate-size compliant balloon may now be advanced over this guidewire to the region of the stenosis and the balloon inflated with a mixture of 50:50 heparinized saline to predilate the lesion. The balloon is then removed. Predilation should be avoided in saphenous vein grafts (if possible) to reduce the risk of distal embolism. Once adequate predilation is performed, a stent of suitable type, size, and length is taken and is flushed to ensure an air-free system. This is advanced over the guidewire across the lesion and deployed by inflating the balloon-mounted stent to appropriate pressures. The stent balloon is now removed, and coronary angiography is performed to ensure no complications and to assess for adequate stent expansion. Some laboratories believe in routine postdilation of all stents (except saphenous vein graft interventions) to ensure adequate strut expansion. If desired, this is accomplished by use of a noncompliant balloon of appropriate size and length. The balloon is removed and coronary angiography is performed in 2 orthogonal views to assess the following: Stent expansion; the proximal and distal stent edges, to ensure no dissections or perforation; and the ostium, to ensure no dissection caused by the guiding catheter.

The guidewire is then removed, and further angiography is performed to confirm adequate stent deployment and no complications, as described above. The guiding catheter should then be removed and intravenous antithrombotic
Coronary Catheter Selection
For routine stenting of noncomplex lesions, a coronary guide catheter of 4F to 6F size is generally recommended. Larger guide catheters (7F to 8F) are needed for more complex procedures (bifurcation stenting, rotational atherectomy, or to provide extra support for chronic total occlusions, tortuous, or calcified lesions). The choice of guide catheter (standard versus support versus extra support) depends on the complexity of the lesion, presence of chronic total occlusions, vessel tortuosity, and calcification, as well as on operator preference.

Coronary Guidewire Selection
The types of guidewires are listed in the accompanying slide set. Some general principles of guidewire selection will be described. It is preferable to always start with the least traumatic wire (workhorse wire) and to always advance the wire under fluoroscopic guidance, ensuring that the guidewire tip does not buckle (more prone to dissection) and that the wire tip is always free. If frequent premature ventricular contractions are noted on wire advancement, the wire tip might have perforated; the wire should be withdrawn slightly. If the wire becomes trapped and is difficult to retrieve (especially in calcified arteries) even with gentle traction, it is best to use a low-profile balloon or small-caliber catheter and advance until the hinge point and then withdraw both as a unit. For stenting over a bifurcation, if a wire is placed in the side branch to protect the branch vessel, the stent can be deployed at low pressures, with withdrawal of the wire in the branch, recrossing through the stent strut, and postdilation to higher pressures. If the wire tip breaks off and embolizes, it potentially can be retrieved with a snare, and if that fails, the embolized tip may be plastered against the wall by use of a stent.

Complications
Apart from the complications listed under diagnostic coronary angiography in the accompanying slide set, those related to PCI include abrupt closure, dissection, perforation, intramural hematoma, side-branch occlusion, distal embolization, ventricular arrhythmia, acute renal failure, radiation injury, myocardial infarction, stroke, emergent coronary artery bypass grafting, and death. Most of these complications can be minimized by appropriate patient selection and with the use of proper catheterization techniques, although they cannot be eliminated entirely. Therefore, great care must always be exercised in deciding to proceed with catheterization and PCI.

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