stress echocardiography, reliable reporting of studies requires considerable experience. A segment of myocardium that is hypokinetic or akinetic at rest represents infarction; a segment that is normal at rest but becomes abnormal during stress represents inducible ischaemia.

Clinical value of MPI and stress echocardiography

For the detection of angiographic coronary stenoses, the sensitivity and specificity of MPI are both about 90%; the sensitivity and specificity of stress echocardiography are 80% and 90% respectively. Both methods provide prognostic information that is independent of angiographic data. A normal study is highly reassuring, and is associated with an annual rate of cardiac death or non-fatal myocardial infarction of less than 1% for MPI and about 2% for stress echocardiography.

Hibernation studies

An increasingly important indication for MPI and stress echocardiography is the identification of patients with myocardial dysfunction at rest that may be improved by revascularization ('hibernating myocardium'). Using gated SPECT, hibernating myocardium takes up tracer at rest while appearing hypokinetic or akinetic. Using dobutamine stress echocardiography, it appears hypokinetic or akinetic at rest, but normalizes with low-dose dobutamine; a subsequent deterioration with high-dose dobutamine ('biphasic response') is particularly predictive. ◆

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Cardiac Catheterization

Douglas Fraser

H Sandmann

J Nolan

Cardiac catheterization involves insertion of a catheter into the heart, through a cannula in a peripheral artery or vein. It is performed under fluoroscopic guidance in a dedicated cardiac catheter laboratory or a shared multipurpose angiography suite. The most common access sites are the right femoral artery and vein. Left heart catheterization involves injection of contrast into the left ventricle (ventriculography) and selective coronary angiography. Pressures in the left ventricle and aorta are also measured. Right heart catheterization involves passing a catheter through the right heart chambers and into the pulmonary circulation, and provides haemodynamic data.

Some of the haemodynamic data obtained rely on several assumptions, and so must be interpreted together with information from other sources and assessment of the patient's clinical condition. Procedure-related complications can occur, and cardiac catheterization should be used only when the results will significantly influence patient management. This contribution concentrates on the role of diagnostic cardiac catheterization in adults.

- Patients with known or suspected coronary artery disease or aortic valve disease usually undergo left heart catheterization, which involves left ventriculography and coronary angiography. Left ventriculography allows visual assessment of left ventricular (LV) function and size, and LV end-diastolic pressure (LVEDP) and the systolic pressure gradient across the aortic valve are measured. Coronary angiography provides information on coronary anatomy. Aortography is also performed in those with aortic regurgitation or aortic root dilatation.

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• Patients with mitral valve disease, heart failure, pericardial constriction or suspected intracardiac shunts usually undergo both right and left cardiac catheterization. Right heart catheterization provides haemodynamic information on right ventricular function, pulmonary artery pressure, right-sided and left-sided filling pressures, cardiac output and left-to-right shunts. Simultaneous left heart catheterization allows assessment of LV and mitral valve function and associated coronary disease.

Procedure

Left heart catheterization

• Left heart catheterization is most commonly performed via a cannula in the right femoral artery. A sheath is inserted using a Seldinger technique, and a side-hole catheter (usually a pigtail catheter) is passed over a J-tipped guidewire to the aortic root and across the aortic valve into the left ventricle. A straight guidewire is used to cross the valve in patients with aortic stenosis, but crossing a severely stenosed valve may be impossible.

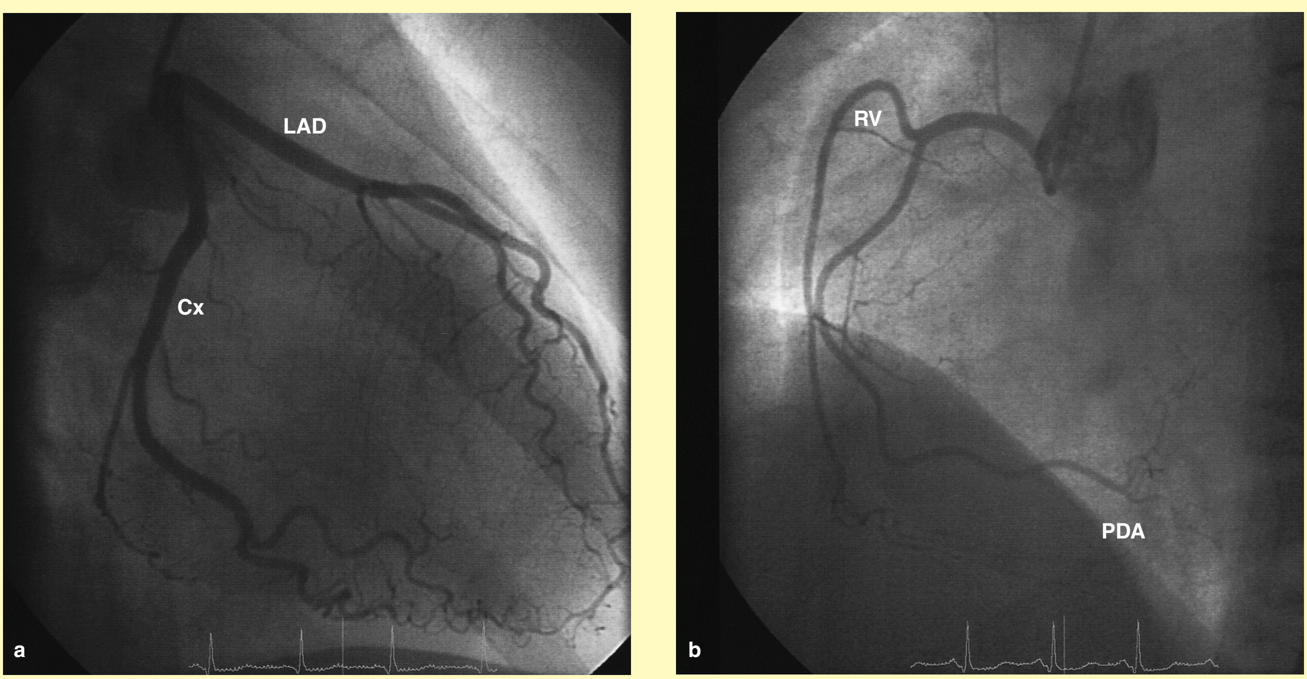
• With the catheter in the left ventricle, the pressure is measured and the end-diastolic pressure is recorded. Ventriculography is performed using a side-hole catheter (usually a pigtail catheter) connected to a mechanical power injector. The pressure is then recorded as the catheter is withdrawn across the aortic valve; a decrease in pressure indicates the presence of aortic stenosis. The catheter may also be placed above the aortic valve and a further power injection performed to image the ascending aorta and assess aortic regurgitation.

• Selective coronary angiography is then performed. In about 90% of diagnostic studies, Judkin's catheters are used. These are end-hole catheters that are designed to engage the coronary ostia with minimal manipulation. In the other 10% of cases, catheters of various shapes are used, depending on the size and orientation of the aortic root and the relative positions of the coronary ostia. The left and right coronary arteries (Figure 1) are imaged in several different projections, using 5–10 ml of contrast injected by hand for each view; typically, six to eight views of the left coronary artery and three of the right coronary artery are obtained.

Alternative access sites are the brachial and radial arteries. Brachial artery access may be achieved using a brachial cut-down procedure or a Seldinger technique. In the cut-down procedure, an incision is made in the skin over the brachial artery and a cannula is inserted via an arteriotomy under direct vision. A medial antecubital vein may also be cannulated for right and left heart catheterization. Radial artery catheterization may be performed if Allen's test demonstrates collateral ulnar circulation to the hand. Access is obtained at the wrist and standard Judkin's catheters may be used.

Right heart catheterization

• The femoral vein is the most commonly used access site for right heart catheterization. A sheath is placed in the vein using a percutaneous Seldinger technique and a pre-shaped end-hole catheter is passed into the right atrium, the right ventricle and a pulmonary artery using standard manipulations under fluoroscopic control. Pulmonary artery pressure is recorded, and the catheter is advanced until it blocks a branch of one of the pulmonary arteries and the waveform changes to a pulmonary capillary wedge (PCW) tracing that closely matches the left atrial pressure.



Coronary angiography of **a** the left and **b** the right coronary arteries. LAD, left anterior descending artery; Cx, circumflex artery; RV, right ventricular branch; PDA, posterior descending artery.

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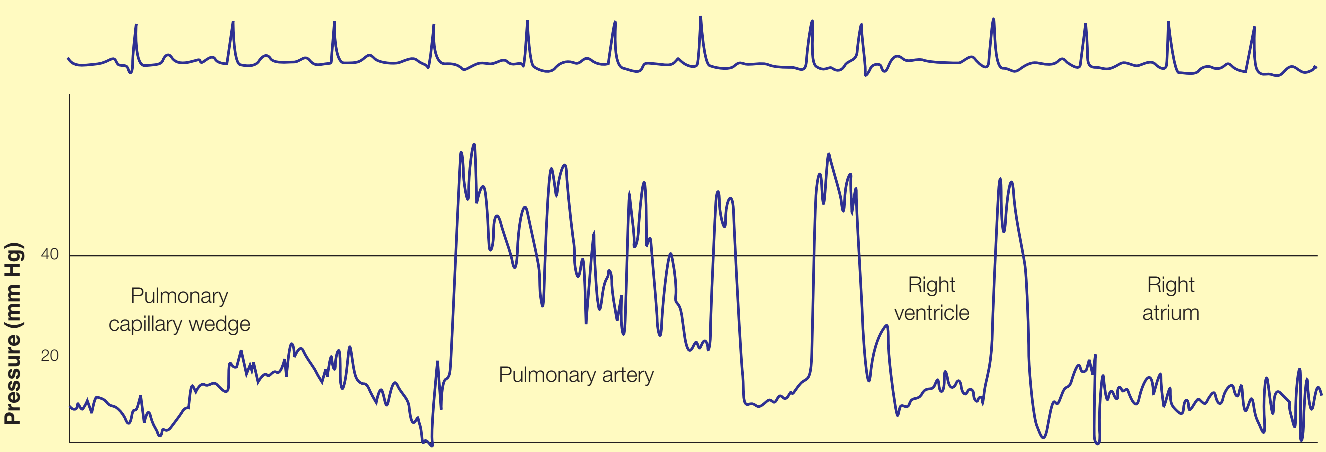
• When mitral valve disease is suspected, simultaneous left heart catheterization is performed and a side-hole catheter is advanced to the left ventricle from a sheath in the right femoral artery. The LV and PCW pressure are recorded; any difference between these measures in diastole indicates mitral stenosis.
• The pulmonary artery catheter is then withdrawn and pressures in the pulmonary arteries, the right ventricle and the right atrium are measured sequentially (Figure 2). Left-to-right intracardiac shunts are assessed using a 'saturation run', in which blood samples withdrawn from the pulmonary artery, the right ventricle, the right atrium and the caval veins are analysed and their oxygen saturations compared.

Flexible balloon-tipped catheters may also be used to measure right heart pressures and cardiac output in ICUs and coronary care units. They are commonly inserted via the subclavian, femoral or jugular vein, and are floated across the tricuspid and pulmonary valves; in many cases fluoroscopic guidance is not needed. With the catheter positioned in the pulmonary artery, cardiac output may be estimated using a thermistor at the tip to measure the thermodilution of a bolus of cold saline injected into the right atrium via a proximal port.

Interpretation of haemodynamic data

• Low PCW pressure or LVEDP indicates hypovolaemia; high values indicate incipient LV failure or fluid overload.
• Raised pulmonary artery pressure (pulmonary hypertension) may result from chronically raised left heart filling pressures in mitral valve disease or heart failure, from long-standing left-to-right shunts, or from intrinsic lung disease. It is an adverse prognostic indicator and indicates increased operative risk.
• Pulmonary vascular resistance is calculated from the trans-pulmonary gradient (mean pulmonary artery pressure minus mean PCW) and cardiac output, and is a critical parameter in the assessment of patients for cardiac transplantation.
• Mitral regurgitation may produce giant 'v' waves in the PCW, and values of 35 mm Hg or more indicate moderate-to-severe regurgitation. This is a useful marker of the severity of regurgitation, but the size of the v wave is considerably affected by left atrial compliance.
• The transmitral gradient (LVEDP minus PCW) is a measure of the severity of mitral stenosis. End-diastolic gradients of more than 5 mm Hg are significant, and gradients of 12–16 mm Hg are typically seen in severe stenosis. However, the size of the gradient depends on heart rate and cardiac output, and this technique has been superseded by echocardiographic criteria. Mitral valve area derived from the Gorlin formula (Figure 3) is more reliable, but requires estimation of cardiac output.
• The pull-back aortic gradient (Figure 4) is an important measure of the severity of aortic stenosis; a gradient of 50 mm Hg or more prompts consideration of valve replacement. Echocardiography measures instantaneous gradients, which are typically 10 mm Hg or more greater than pull-back gradients, and this may lead to significant overestimation of the severity of aortic stenosis. However, if LV function is poor, the pull-back gradient is reduced, and estimation of valve area using echocardiography or the Gorlin formula is a more accurate guide to severity.
• Left-to-right intracardiac shunts are assessed by comparing oxygen saturations in the superior vena cava, the inferior vena cava, the high, mid and low right atrium, the right ventricle and the pulmonary artery. An increase in saturation of more than 7% suggests a left-to-right shunt. Small shunts may not be detected. The magnitude of the shunt is measured in terms of the relative blood flows in the systemic and pulmonary circulations.
• Cardiac output is measured using a thermodilution method or by the Fick principle. The Fick principle calculates cardiac

Right heart withdrawal in a patient with mild pulmonary hypertension



Normal values
• Right atrium mean < 5 mm Hg
• Right ventricle < 25 mm Hg systolic, < 5 mm Hg diastolic
• Pulmonary artery < 25 mm Hg systolic, < 10 mm Hg diastolic
• Pulmonary capillary wedge mean 4–12 mm Hg, left ventricular end-diastolic < 10 mm Hg

3

Formulae used for haemodynamic data

- Left-to-right shunt $\dfrac{\text{Pulmonary flow}}{\text{Systemic flow}} = \dfrac{SAO_2 - MVO_2}{98 - PAO_2}$

  SAO_2, aortic oxygen saturation; PAO_2, pulmonary artery saturation
  MVO_2= (3 x superior vena cava saturation + inferior vena cava saturation)/4

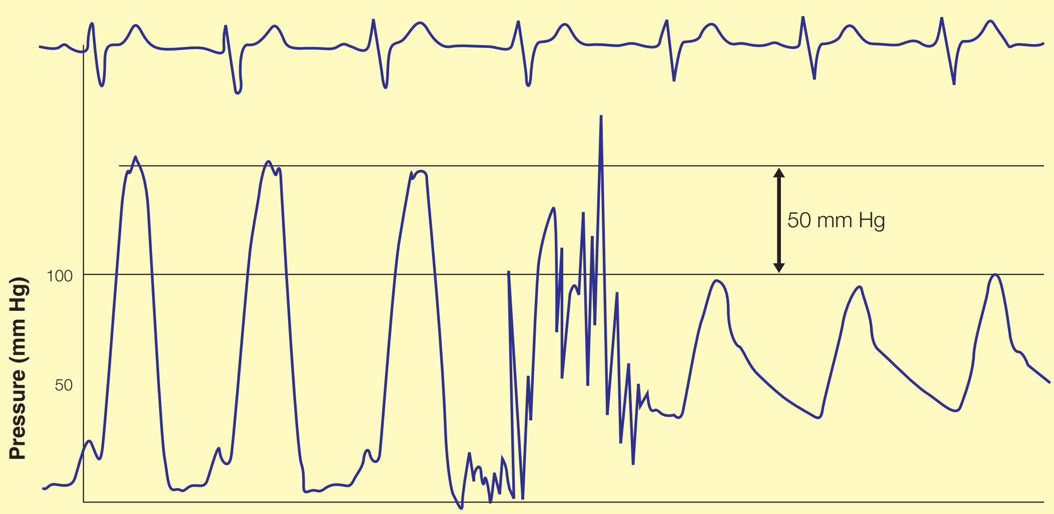
- Aortic valve area (cm^2) (Gorlin formula) $\dfrac{\text{Cardiac output (litres/minute)}}{\text{Opening time/beat} \times \text{heart rate} \times \sqrt{\text{mean gradient (mm Hg)}} \times 44{\cdot}3}$

- Mitral valve area (cm^2) (Gorlin formula) $\dfrac{\text{Cardiac output (litres/minute)}}{\text{Opening time/beat} \times \text{heart rate} \times \sqrt{\text{mean gradient (mm Hg)}} \times 37{\cdot}7}$

- Cardiac output (litres/minute) (Fick principle) $\dfrac{\text{Oxygen consumption (ml/minute)}}{1.36(SAO_2 - PAO_2) \times \text{haemoglobin concentration (g/litre)}}$

3

Pressure during pull-back across the aortic valve, showing a peak-to-peak gradient of 50 mm Hg



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output from oxygen consumption (measured using a metabolic hood or a Douglas bag) and the arteriovenous difference in oxygen content (measured from blood samples taken in the pulmonary artery and aorta). Alternatively, oxygen consumption can be estimated as 3 ml O_2/kg body weight, but this is less accurate.

Complications

Minor complications such as vasovagal reactions and urticaria occur in about 5% of patients. Major complications such as major haemorrhage, myocardial infarction, stroke, major arrhythmia or death occur in 0.25% of patients, and are more common in those with advanced cardiac disease. There are fewer access site complications when the radial artery is used. ◆

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(A useful review of the complications of cardiac catheterization.)

Practice points

- Cardiac catheterization provides comprehensive assessment of left and right heart anatomy and function
- Despite the development of non-invasive tests, cardiac catheterization remains an essential investigation in many cardiac disorders
- Haemodynamic parameters are affected by physiological conditions, and must be interpreted in light of this and together with complementary information
- Cardiac catheterization is an invasive test with potentially major complications and so must be performed only when the results will influence management

MRI and CT

Stefan Neubauer

The investigation of patients with cardiovascular disease should provide information on both the anatomy and the physiology of the heart and vessels, including the three-dimensional anatomy of the heart and its surrounding structures, global and regional pump function, blood supply and regional viability. The three main modalities currently used in cardiology (echocardiography, cardiac catheterization and nuclear methods) provide only limited information on the pathophysiological state of the heart. In recent years, major technical progress has been achieved in cardiac MRI and CT, and these methods may allow complete and non-invasive multiparametric characterization of the cardiovascular system.

There are currently few accepted indications for MRI and CT in cardiology, and routine clinical applications (e.g. for the diagnosis of coronary artery disease) require substantial further development. However, it is likely that MRI, and, to a lesser extent, CT will become standard diagnostic methods in cardiac patients.

Background

MRI is usually based on the magnetic properties of the hydrogen nucleus, though other nuclei can be used. In an MRI examination, the patient is placed in a powerful magnetic field with which the protons in the body become aligned. Radio waves in the form of a radiofrequency pulse transmitted into the patient cause the alignment of the protons to change (e.g. by 90°). When this radiofrequency pulse is turned off, the protons in the patient's body return to their neutral position, emitting their own weak radio-wave signals, which are detected by receiver coils and used to produce an image. The phase and amplitude of each returning radio-wave signal can be determined using powerful computers and additional magnetic field gradients, and this information can be used to map the position of the excited protons. The resulting image reflects not only proton density, but also the highly complex manner in which protons resonate in their local environment. Cardiac MRI requires advanced technology, including a high-field magnet (typically 1.5 Tesla), fast-switching gradient coils, and coils for transmission and signal reception.

Both CT and conventional MRI scans comprise an array of small picture elements (pixels), but the distinction between different tissues (contrast resolution) is greater in MRI. In CT, the attenuation value of each pixel reflects only the local tissue density. In MRI, the equivalent value is influenced by

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