Chapter

32 Anaesthesia for Cardiac Catheterisation and Other Investigative Procedures in Children*

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Introduction

Since the publication of the previous edition of this chapter, the principles of caring for children in the cardiac catheterisation laboratory (cath lab) remain much the same. Advances in technology and novel devices allow catheter-based interventions in increasingly complex cases of congenital and acquired heart disease, often replacing or postponing the need for a surgical approach. Even extremely preterm infants (some less than 800 g) can now be offered interventional procedures in the catheter lab. Conversely, there is a reduced need for cardiac catheterisation as a purely diagnostic tool, as non-invasive imaging modalities such as cardiac CT and MRI continue to increase in their application and sophistication.

The anaesthetist may find themselves undertaking high-risk, complex cases, with challenges inherent to the cath lab, in a location which may be remote from the main theatre suite. Anaesthetists managing children with complex congenital cardiac disease must understand the pathophysiology of these patients and the effects that anaesthesia and any intervention will have on their underlying physiology. Table 32.1 lists cardiac catheter laboratory procedures.

Table 32.1 Cardiac catheter laboratory procedures

	Procedure
Diagnostic	Diagnostic catheter/ angiography Coronary angiography Endomyocardial biopsy Pulmonary vascular resistance study Transoesophageal echocardiography
Interventional	Septal defect closure Vessel occlusion Balloon valvotomy Balloon angioplasty Stent placement Balloon atrial septostomy Percutaneous valve implant
Electrophysiological studies (EPS)	Conduction system mapping Ablation of arrhythmogenic focus Pacemaker insertion Loop recorder insertion Placement of implantable cardioverter defibrillator (ICD) Cardioversion
Miscellaneous	Drainage of pericardial effusion

Risk

Data from the Pediatric Perioperative Cardiac Arrest Registry show that children with congenital heart disease account for nearly a third of perioperative arrests. Paediatric cardiac catheterisation carries a risk of cardiac arrest of around 0.8% and a mortality risk of 0.2%. This is significantly higher than routine paediatric anaesthesia (about 20 times higher). Scoring systems have been developed to help quantify this risk, such as the Catheterisation Risk Score for Pediatrics (CRISP; see 'Further Reading'). Risk factors which increase the likelihood of a life-threatening event during cardiac catheterisation include:

- Age less than one year
- More than two haemodynamic indicators of vulnerability (low mixed venous saturations,

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elevated systemic ventricle end-diastolic pressure, low systemic arterial oxygen saturation, elevated pulmonary artery pressure)
- Greater procedural complexity (valvuloplasty, pulmonary artery stent placement, ventricular septal defect closure)

Particular attention must be given to children on a single ventricle pathway, those with a cardiomyopathy and children with pulmonary hypertension. These groups have the highest anaesthesia-related mortality in paediatrics.

Environment

The cath lab environment itself may add to the difficulty managing clinically challenging cases. It is often an isolated suite, away from the operating theatres and the support of anaesthesia personnel and resources, with the additional challenge of limited functional space. There may be reduced access to the patient once the procedure is under way, with imaging equipment hindering airway manoeuvres or additional vascular access, which in an emergency can be troublesome. Long anaesthesia circuits are required to reach the patient, and this should be taken into account when ventilating infants. It is important to identify those cases in which it is prudent to have additional expertise present for the case.

Temperature regulation must be considered. Small babies, particularly premature infants and neonates, lose heat very quickly under anaesthesia. Forced-air warmers, fluid warmers and warming mats should be used to maintain normothermia.

Staff working in the cath lab must keep safe from radiation exposure and wear protective shielding (wraparound lead aprons, thyroid guards and eye shields). Dosimeter badges should be worn to monitor cumulative radiation exposure, and attempts should be made to stay as safe as possible by using mobile lead screens and minimising exposure time.

World Health Organisation Checks and Briefs

Crucial to a successful cardiac catheter procedure is the preoperative discussion, or brief. There may be a large team of interventionalists, anaesthetists, anaesthetic assistants, scrub nurses, running nurses, physiologists, radiographers and observers. In some cases, a full cardiac theatre team is also present. The brief should include introductions, presentation of the patient's history (led by the operator), the intended procedure, any special requirements, discussion of risk and complication management during the procedure, any additional staff that may need to be called, the need for and location of blood products, potential need for an intensive care bed or other escalations and other factors, including pregnancy test results and infectious alerts. A routine 'sign in' should be performed before induction of anaesthesia. The routine 'time out', which re-confirms the patient identity, consent and preparation for the procedure, should include checks such as the presence of distal limb pulses and pressure area protection, and whether there are new members of the team who were missing from the initial brief. During the procedure, it may be necessary to call out an update, especially if there is a complication or a change of plan, because the events may not be immediately evident to the whole team. An interim check is necessary if additional procedures are planned, such as magnetic resonance scanning, in which case a full metal compatibility check must be completed. After the procedure, with the instrument and swab counts completed, a 'sign out' is performed and recorded before the child is woken up or taken to ICU.

Diagnostic Cardiac Catheterisation

Diagnostic catheterisation is performed to collect data regarding the child's cardiovascular anatomy, haemodynamics, cardiac function and response to administered medications. Measurement of arterial, mixed venous, pulmonary venous and pulmonary arterial oxygen saturations allows determination of blood flow using the Fick principle. If oxygen consumption is measured, systemic blood flow (Qs), pulmonary blood flow (Qp) and the pulmonary to systemic flow ratio, commonly referred to as Qp:Qs, can be calculated (Box 32.1). In a normal series circulation, cardiac output equates to Qs; in patients without a cardiac shunt, Qp and Qs should be equal. Shunt lesions (septal defects, ducts, surgical shunts, collateral arteries) will alter this ratio. In patients with a parallel circulation, such as single ventricle, cardiac output will equal Qs + Qp.

Measurement of oxygen consumption is difficult and requires a mass spectrometer and a sealed

Box 32.1 Haemodynamic calculations.

Haemodynamic variable	Normal values
Flow *(based on the Fick equation)*	
Systemic output (Qs) = $VO_2/(C_{ao}O_2 - C_{mv}O_2)$	**3.5–5 (l min^{-1} m^{-2})**
Pulmonary flow (Qp) = $VO_2/(C_{pv}O_2 - C_{pa}O_2)$	**3.5–5 (l min^{-1} m^{-2})**
Shunt fraction:	
Because of the technical difficulties of measuring oxygen content for shunt calculation, in practice shunt fraction is often calculated using saturation measurements from a number of different sites by the following equation:	
Pulmonary to systemic (Qp:Qs) = $(S_{ao}O_2 - S_{mv}O_2)/(S_{pv}O_2 - S_{pa}O_2)$	**1:1–1:1.2**
Mixed venous saturation ($S_{mv}O_2$) can be approximated from:	
$[3(S_aSVC) + (S_aIVC)]/4$	**0.65–0.75**
Resistance:	
Pulmonary (PVRI) = (PAP – LAP)/Qp	**Newborn 8–10 Woods units m^2**
(common to substitute PA wedge for LAP)	**Older children 0.6–2 Woods units m^2**
Systemic (SVRI) = (AoP-RAP)/Qs	**Newborn 10–15 Woods units m^2**
(note indexed resistance is expressed as Wood units•m^2, not Wood units m^{-2}. This is because the denominator (Qp or Qs) is already an indexed value, calculated by absolute flow/BSA.	**Older children 15–30 Woods units m^2**

Notes: VO_2 = oxygen consumption; CO = cardiac output; $CaoO_2$ = aortic arterial oxygen content; $CmvO_2$ = mixed venous oxygen content; SO_2 = oxygen saturation; Qp = pulmonary flow; Qs = systemic flow; ao = aorta; mv = mixed venous; pa = pulmonary artery; pv = pulmonary vein; Hb = haemoglobin; PVR = pulmonary vascular resistance, PVRI = indexed pulmonary vascular resistance; PAP = pulmonary artery pressure; SVC = superior vena cava; IVC = inferior vena cava; SVR = systemic vascular resistance; RAP = right-atrial pressure; LAP = left-atrial pressure; AoP = aortic pressure

ventilator system to allow collection of all expired gases. Alternatively, standard assumed values of oxygen consumption are commonly used, though the available nomograms have been shown to be very inaccurate. Thermodilution is an alternative method of determining cardiac output, although this cannot be used in the presence of a cardiac shunt. MRI provides gold standard flow measurements but is only available in specialised centres (see the section 'Cardiac MRI and CT').

Catheterisation data often form the basis for important decisions, for instance whether a patient is suitable for cardiac transplantation or closure of a shunt lesion such as a ventricular septal defect. It is important that the physiological state of the patient remains constant during the procedure; the inspired oxygen fraction, ventilation and depth of anaesthesia should remain stable. If changes to these parameters are made, it is important for the anaesthetist to communicate these to the cardiologist, to determine whether the physiological measurements need to be repeated under constant conditions.

Direct pressure and flow measurements can provide calculation of systemic and pulmonary vascular resistance (Box 32.1). Cardiac output (CO) can be indexed to body surface area (BSA) such that the Cardiac Index (CI) = CO/BSA. Absolute pulmonary vascular resistance (PVR) is referred to in Wood units, but indexed PVR (PVRI) is referred to in Wood units m^2 (because PVRI = PVR/CI, or PVRI = PVR/CO/BSA). Indexed PVR would usually be under 2 Wood units m^2 in health. Intracardiac and intravascular pressure measurements also provide information about cardiac function and obstructions to flow across valves and vessels and are more accurate than those derived using echocardiography.

Additional diagnostic information is obtained with angiography, which involves the injection of radiographic contrast medium to outline heart structures, great vessels, venous connections and any abnormal vessels such as collaterals or malformations. This can be crucial in establishing the exact anatomical nature of some complex cardiac anomalies. Coronary angiography may be

undertaken when echocardiography is unable to answer concerns about coronary anatomy or perfusion. Coronary artery disease is the most common complication of cardiac transplantation, and coronary angiography is part of the routine interval follow-up of these patients. Contrast medium is iodine-based and of varying osmolarity. Hyperosmolar solutions are avoided in children, as they are associated with flushing, hypotension, bradycardia and renal impairment. Adequate hydration is essential in children undergoing angiography, particularly those with pre-existing renal dysfunction, because of the small risk of contrast-induced nephropathy. Anaphylaxis to contrast can occur but is rare. Where contrast allergy exists, an alternative is angiography with carbon dioxide which is rapidly absorbed into solution before embolic phenomena may occur. Intravascular ultrasound (IVUS) uses a fine intracoronary ultrasound catheter to identify early plaque formation within the coronary arteries. It may be utilised in children over 20 kg.

Interventional Cardiac Catheterisation

Interventional procedures involve the introduction of a variety of devices into the heart or major vessels. These may be:

- Balloons, which are expanded with contrast solution to dilate valves or vessels.
- Stents – balloon-expandable or self-expanding which are implanted to widen a vessel.
- Devices that can be deployed to occlude septal defects, paravalvar leaks, collaterals and other vessels.
- Coils, positioned to occlude vessels such as a patent arterial duct and collateral arteries or veins.
- Artificial valves – transluminal implantation of a valve, such as the Melody Valve® (pulmonary valve) or an aortic valve in adults (transcatheter aortic valve implantation, or TAVI). Off-license use of devices and valves are occasionally considered, for instance the Melody Valve® in the tricuspid position.

Access to the Heart and Major Vessels

The right side of the heart and pulmonary arteries are accessed via the femoral vein, the jugular vein or occasionally the hepatic vein. The internal jugular vein is preferred for endomyocardial biopsy as it provides easier access to the right ventricle and may be necessary in other cases if the femoral or iliac vessels are blocked. Internal jugular, axillary or subclavian vein access will also be required if it is necessary to measure the pressure in the pulmonary artery after a Glenn anastomosis (in which the SVC is connected to the pulmonary artery).

The left side of the heart and major arterial vessels are usually accessed from the femoral artery or from the right side of the heart via a septal defect or trans-septal puncture. The cardiologist may insert a femoral arterial monitoring line even when left heart catheterisation is not planned. In the absence of an atrial septal approach, it can be difficult and arrhythmogenic to pass a catheter retrogradely across the mitral valve, and so an alternative, indirect method of assessing left-atrial pressure is the pulmonary capillary wedge pressure (more accurately known as the pulmonary *arterial* wedge pressure). This is obtained by wedging a balloon-tipped catheter into a pulmonary artery and measuring the pressure distal to the balloon. This is commonly used for left-atrial pressure for calculation of transpulmonary pressure or pulmonary vascular resistance.

Introducer sheaths are placed using the Seldinger technique under ultrasound guidance. These allow catheters to be inserted without loss of blood or introduction of air. Relatively large sheaths are sometimes required for implantation of larger devices, and the sheath may need to be upsized during the case. Heparin, 50–100μ kg^{-1}, is given to prevent thrombosis for most cardiac catheter procedures and particularly when systemic arterial or left-atrial catheters are employed. Monitoring of adequate anticoagulation is performed using activated clotting times (ACT). At the end of the procedure, it is important that satisfactory haemostasis at the puncture site is achieved before anaesthesia is terminated, as it can be very difficult to control bleeding in a restless, wakening child.

Anaesthesia

Cardiac catheterisation is seldom painful, apart from the infiltration of local anaesthetic and the placement of an introducer sheath in a vessel, which is usually the most stimulating time for a

patient. In older children, some diagnostic procedures can be undertaken under local anaesthesia, supplemented with light sedation if necessary. However, in paediatrics, general anaesthesia is necessary for most cath lab procedures, especially if prolonged.

In the majority of cases, the requirement from the anaesthetist is for a still patient with stable haemodynamics, preferably with parameters as near to normal as possible. Inappropriate anaesthesia and ventilation can adversely affect the haemodynamic data being collected, so the anaesthetist must have a thorough knowledge of these potential changes as well as of the procedures being performed. For example, oxygen saturation data for accurate blood flow measurement are best achieved with inspired oxygen as near to 21% as can be tolerated. Normocapnia is particularly important when pulmonary vascular resistance is being assessed. Hypovolaemia and hypotension may lead to inaccurate determination of flows and shunts. Good communication with the cardiologist is essential.

Induction

Where possible, full anaesthetic monitoring should be applied before induction. Inhalational or intravenous induction is suitable for cardiac catheterisation and will usually depend on the child's age and preferences. Sevoflurane is the ideal agent for inhalational induction. For intravenous induction, propofol is usually suitable unless a fall in SVR is to be avoided, in which case ketamine may be preferred. In patients with limited cardiac output reserve, such as dilated cardiomyopathy, it is important that blood pressure and coronary perfusion do not fall during induction. A combination of fentanyl 1–2 mcg kg^{-1} and propofol 1–2 mg kg^{-1}, titrated gently, works well.

As most procedures are conducted through femoral vessels, it is generally preferable to avoid the lower-limb veins for venous access.

Airway Management

A supraglottic airway device (SGA) may be appropriate for many straightforward diagnostic cases in older infants and children. For small infants, patients who are clinically unstable and those undergoing interventional procedures, a tracheal tube should be employed. Intubation may be preferred for patients in whom internal jugular venous access is required. If the cardiologist needs to collect all expired respiratory gases to measure oxygen consumption, a cuffed tracheal tube should be used. A cuffed tube will also be advantageous when it is necessary to ensure steady carbon dioxide tension during pulmonary vascular resistance studies.

Controlled ventilation is indicated in most cases, as it allows careful control of the blood gases for haemodynamic data collection and facilitates the short periods of apnoea that are occasionally necessary for accurate pressure measurement and high-quality angiographic pictures.

Maintenance

Maintenance of anaesthesia with inhalational agents is typically with isoflurane or sevoflurane, which are usually well tolerated and are the volatile agents of choice. Total intravenous anaesthesia (TIVA) has become increasingly popular, with an increased focus on delivering an environmentally friendly anaesthetic. Nitrous oxide should be avoided during cardiac catheterisation.

A small dose of fentanyl (1–2 mcg kg^{-1}) may be given before inserting a transoesophageal echocardiography (TOE) probe, to blunt the pressor response it induces. Opioid analgesics are otherwise seldom required. Many procedures are undertaken as day cases, so a plan for post-discharge analgesia should be made. Long-acting local anaesthetic infiltration to the puncture site is usually adequate for post-catheter pain relief along with paracetamol, given either intravenously during the procedure or orally afterwards. There is a significant incidence of nausea and vomiting following inhalational anaesthesia for cardiac catheterisation despite avoidance of opioids, and antiemetics should be given.

Monitoring

Full monitoring should be used for all catheterisation procedures. Multi-lead ECG is generally part of the routine cardiac electrophysiological data displayed, so a separate anaesthetic ECG is not usually required after induction. Distal perfusion can be impaired in the limb used for catheter access; non-invasive blood pressure and pulse oximetry should be applied to the contralateral leg or the upper limbs. End-tidal CO_2 can be significantly affected by cyanotic heart disease, owing to venous admixture and impaired pulmonary blood

flow, and may underestimate $PaCO_2$ by up to 2 kPa. In general, the greater the degree of cyanosis, the greater the end-tidal to arterial pCO_2 gradient. Invasive blood pressure monitoring is seldom required in diagnostic catheterisation but may be indicated in unstable patients or those with severe pulmonary hypertension. Depth of anaesthesia monitoring should be used if neuromuscular blocking agents are administered together with TIVA.

Intravenous fluids are required for all but the shortest procedures, especially if contrast is being used.

Positioning

For most procedures where biplane X-ray imaging is used, the patient is positioned supine with the arms above the head. Care must be taken that the brachial plexus is not stretched. Exposure is less than during surgical procedures, but temperature monitoring and active warming should be available. Procedures can take many hours and pressure areas must be protected. In some procedures, for instance carotid access procedures, the head-toe position may be reversed, and particular attention must be paid to the placement of the breathing system and intravenous lines. For patients on extracorporeal membrane oxygenation (ECMO), there can be significant challenges in transferring the patient safely on to the X-ray table in such a way as to permit satisfactory fluoroscopy, adequate access for the anaesthetist and interventional cardiologist and very occasionally for the cardiac surgical team.

Interventional Procedures

When an intervention involves inserting a device, the cardiologist may request that the anaesthetist give antibiotics according to the local guidelines. This will be discussed at the preoperative brief.

- *Device closure:* Device closure of an arterial duct, atrial or ventricular septal defect, are commonly performed interventional procedures. Patients are usually well, and the procedure is generally straightforward. TOE is useful to ensure correct placement of atrial septal defect (ASD) and ventricular septal defect (VSD) devices, less commonly for duct occlusion. Care must be taken to monitor that the TOE probe does not compress the tracheal tube and impair the ventilation of the patient. Rarely, device displacement may occur and complications develop according to the site of displacement. For instance, an atrial septal occluder may displace and impinge on an atrioventricular valve. Mostly, device displacements can be managed by retrieval using endovascular techniques, but occasionally urgent open-heart surgery is necessary for retrieval. Transcatheter closure of a VSD is technically more challenging and is associated with more complications, particularly heart block and valve damage. During any procedure involving stiff catheters and wires crossing the tricuspid valve, transient hypotension can occur.
- *Vascular occlusion*: This is performed for aorto-pulmonary collaterals or veno-venous connections. These patients are usually relatively well, although on occasion there can be a degree of high-output failure. Again, there is always the risk of the occlusion device embolising, necessitating retrieval.
- *Valvotomy:* This may be carried out in the early neonatal period for critical pulmonary valve stenosis or for critical aortic valve stenosis. Both these groups of patients can be seriously ill and may have a duct-dependent circulation, requiring a prostaglandin infusion to maintain ductal patency. In both procedures, a balloon is dilated across the valve for several seconds, resulting in a short period of absent cardiac output.
- *Critical aortic stenosis:* This has a significant risk of cardiac arrest during the procedure, due to catheter- or wire-induced ventricular fibrillation. There is usually a hypertrophied and poorly functioning left ventricle, and inflation of the balloon tends to obstruct coronary perfusion. Volatile agents are poorly tolerated, and it is our practice to use high-dose fentanyl and oxygen. Hypovolaemia is also poorly tolerated, and inotropic support may be necessary. Resuscitation drugs should be close at hand. Balloon dilatation can cause acute aortic regurgitation, which may ultimately need surgery, though this would usually be tolerated acutely. These patients will nearly always need pre- and postoperative intensive care support. Emergency ultrasound-guided transcarotid aortic valvotomy has been performed in patients too unstable to move to the cath lab.

- *Critical pulmonary stenosis:* There will be profound cyanosis as a result of right-to-left shunting across the atrial septum, and acidosis is common. The pressure-loaded right ventricle may be poorly functioning and may be further compromised during occlusion of the pulmonary valve. Pulmonary regurgitation may be produced, though this is better tolerated than aortic insufficiency. The hypertrophic right ventricle may need a high filling pressure after relief of the afterload; vasodilators and aggressive diuresis should be avoided, and occasionally beta blockade is employed.
- *Balloon dilatation:* Such dilation of the aortic and pulmonary valves may be necessary in older children, and the greater the obstruction the greater the likelihood of ventricular hypertrophy and dysfunction.
- *Angioplasty and stent placement*: Re-coarctation of the aorta, pulmonary artery stenosis or narrowing of the superior vena cava may be treated with balloon angioplasty. It may be necessary to place an endovascular stent to maintain adequate vessel patency, although this necessitates a larger introducer sheath, with a higher risk of vascular damage. Acute complications include rupture of the vessel being dilated, which may require management with balloon tamponade, implant of a covered stent or urgent surgery. Most centres will ensure that surgical cover is provided. Although rare, there is the possibility of displacement and embolisation of the stent.
- *Infant right-ventricular outflow tract stent*: This procedure has become more established to protect pulmonary blood flow in patients with tetralogy of Fallot. Access is via the femoral or internal jugular vein. During the procedure, there may be profound cyanotic spells and low cardiac output because of splinting of the tricuspid valve. The procedures can be challenging because the delivery of the stent requires an introducer sheath to be advanced into the pulmonary artery.
- *Neonatal ductal stent*: In patients with duct-dependent systemic or pulmonary blood flow, ductal stenting may be considered. A ductal stent to maintain pulmonary blood flow is intended to be restrictive, to prevent over-circulation of the lungs. A ductal stent to maintain systemic blood flow must be unrestrictive and is usually done as a hybrid procedure, in conjunction with bilateral pulmonary artery banding performed by the surgeons.
- *Neonatal balloon atrial septostomy (BAS):* In transposition of the great arteries (TGA), it is essential that there is adequate mixing of systemic and pulmonary venous blood in the period prior to surgery. Where this is inadequate it will be necessary to create a communication at atrial level. This is performed by passing a balloon-tipped catheter across from the right to left atrium through the foramen ovale, inflating it and then withdrawing it sharply back into the right atrium, tearing the septum in the process. It may be necessary to repeat this a few times to achieve an adequate communication. These neonatal patients may be extremely cyanosed and acidotic, but rapidly improve once the septostomy is performed. In an already ventilated patient, it is most common to undertake these cases at the bedside on the ICU under echocardiographic guidance. Neonates who are not intubated will require an anaesthetic to allow the procedure to take place, usually in the cath lab with ultrasound guidance or even full radiological imaging.
- *Atrial septal puncture and atrial septostomy*: In patients with severe pulmonary hypertension, it may be beneficial for them to have an atrial communication; this allows decompression of the right side of the heat and augmentation of left-sided filling to maintain cardiac output during times of pulmonary hypertensive crisis. Atrial septal puncture may be performed in the cath lab, followed by graded balloon dilatation of the atrial septum. These patients are at high risk for adverse cardiac events under anaesthesia, and the procedure carries additional risk because of the orientation of the atrial septum bowing towards the free wall of the left atrium.
- *Percutaneous valve placement*: The development of a percutaneously implanted pulmonary valve, fashioned from a platinum/iridium alloy stent containing bovine jugular vein valve (the Melody Valve®), has revolutionised the management of right-ventricular outflow tract dysfunction (stenosis or regurgitation) which would otherwise require major open-heart surgery. There is a

risk of device migration and damage to intracardiac structures and vessels. The cardiologist will carefully assess the proximity of the coronary arteries because of the risk of coronary artery distortion as the stent is implanted. If the coronary arteries are deemed too close, the procedure will be abandoned.

Hazards/Complications

Although most diagnostic procedures are uncomplicated, for some children the nature of the cardiac lesion being investigated is such that induction of anaesthesia may be hazardous. For example, a fall in systemic vascular resistance or blood pressure in children in whom coronary perfusion is borderline can lead to significant haemodynamic compromise and cardiac arrest. Infants with severe pulmonary hypertension and cardiomyopathy are particularly vulnerable.

In addition to the risks of device embolisation already mentioned, there are several potential complications associated with cardiac catheterisation in general:

- *Dysrhythmias:* Atrial and ventricular arrhythmia can be precipitated by the manipulation of catheters within the heart. Repositioning of the catheter may resolve the problem, but occasionally DC cardioversion may be necessary. Heart block can occur as the atrioventricular (AV) junction is navigated, particularly in AV discordant circulations, and will usually settle over a few minutes, though on occasions it can last longer. Pacing facilities must always be available in the cath lab but are usually not needed.
- *Coronary ischaemia:* During coronary angiography, ischaemic changes may rarely be encountered. They are most likely to be related to deep intubation of the coronary artery, or coronary spasm. If these changes do not resolve following repositioning or withdrawal of the catheter, glyceryl trinitrate (GTN) can be administered directly into the coronary artery. During IVUS, intracoronary GTN is given before the guidewire is passed to allow introduction of the IVUS catheter. The small dose, given locally, is unlikely to create a systemic effect.
- *Hypotension:* This can be caused by hypovolaemia, rhythm disturbances or impaired ventricular function exacerbated by volatile anaesthetic agents.
- *Impaired cardiac output*: Balloon dilatation of aortic or pulmonary valve stenosis will totally obstruct flow from the ventricle. This is for a few seconds only and is usually well tolerated. On occasion it can lead to profound decompensation and cardiac arrest.
- *Hypoxaemia:* Passing catheters into vessels that are the only or the main source of pulmonary blood flow can lead to profound desaturation.
- *Perforation of cardiac chambers or major vessels:* Although rare, it is important to consider the possibility of perforation of a cardiac chamber resulting in tamponade, or of a major vessel, if there is an otherwise unexplained fall in blood pressure or signs of reduced cardiac output during or after the procedure. An echo should be obtained urgently to assess this. Retroperitoneal haematoma from a perforation in the abdominal or iliac vessels should also be considered, particularly if there has been difficulty advancing a catheter from the femoral vessels.
- *Vascular injury:* Thrombosis of the artery used for catheterisation is a known complication, despite the use of heparin administered at the time of catheterisation. Regular assessment of the limb pulses and temperature is an important part of routine postoperative management, and there should be a protocol in place for the management of a limb with signs of arterial insufficiency.
- *Haematoma:* This may occur at the site of vascular access at the end of the procedure or several hours later, particularly if heparin has been given.

Premature Infants

Cardiac catheterisation in premature infants is becoming more common. Transcatheter duct occlusion is now available from three days of age and 700 g weight. Anaesthetic equipment may be less suited for use in babies less than 1 kg, and careful planning between the neonatal service and the anaesthetist is necessary. A neonatal ventilator may be needed (particularly in the presence of premature lung disease), which may affect the way the anaesthetic is planned and delivered. Transport of the infant between the cath lab and

neonatal unit needs to be carefully planned. Vascular access can be challenging. Other considerations include temperature control (e.g. warming intravenous fluids, use of heating mats), avoidance of over-hydration and monitoring blood glucose. The cardiologist may also ask for a nasogastric tube or oesophageal temperature probe to be present as a radiographic landmark.

Hybrid Procedures

Hybrid procedures describe those involving either a cooperative approach by cardiologists and surgeons, or a combined radiological imaging procedure.

Hybrid surgical procedures can be challenging and require coordination between the many members of the different teams at the preoperative brief. Examples of surgical hybrid procedures include the hybrid Norwood operation, which involves direct pulmonary artery branch banding by the surgeon, and the implantation of a ductal stent by the cardiologist, often via direct puncture of the pulmonary artery. Other examples include per-ventricular closure of a ventricular septal defect and direct stent implantation into the pulmonary artery right-ventricular outflow tract. Repair of left pulmonary artery sling in our centre has evolved into a hybrid procedure, involving the cardiology team, to include an exit epicardial echocardiogram and angiogram.

Hybrid imaging procedures may involve catheters being positioned conventionally in the fluoroscopy facility and then moving the patient with catheters in situ into the MRI suite. This allows the combination of pressures and MRI data to be collected simultaneously, such as for the accurate assessment of PVR. A standardised system of checks for safety is necessary, including the exclusion of metallic objects from the field and ensuring the security of fluid-filled monitoring tubes through which significant bleeding could occur should they become disconnected.

Electrophysiological Studies

Children present for electrophysiological studies (EPS) to identify the source of an arrhythmia and potentially to ablate an abnormal focus or pathway. Most of these patients have normal ventricular function, and many suffer from paroxysmal supraventricular tachycardias. Most commonly these are re-entry or accessory pathway tachycardias such as sinoatrial node re-entrant tachycardia (SARNT), atrioventricular (AV) nodal re-entrant tachycardia (AVRNT) or Wolff–Parkinson–White syndrome and atrioventricular re-entry tachycardia (AVRT).

The procedure involves the insertion of catheters with multiple electrodes along their length into the coronary sinus via the right heart, to stimulate and map the electrical pathways. Access can be from the femoral or subclavian vein. Once the abnormal pathway has been identified, it is ablated by radio-frequency energy delivered by another catheter. The size of the 'burn' necessary to fully ablate the focus varies and the procedure can be prolonged. Where the abnormal focus lies close to the AV node, radiofrequency carries a high risk of heart block; a newer technique involving cryoablation with a super-cooled catheter appears to be safer, though recurrence risk is higher.

Anaesthesia is generally straightforward, as these children are usually otherwise well. Many arrhythmias are provoked by stress and suppressed by deep anaesthesia; the latter should therefore be avoided, as it may make it more difficult to identify the focus. TIVA is a good option, combined with depth of anaesthesia monitoring to avoid excessively deep anaesthesia. Isoflurane at 1–1.5 MAC supplemented with a small dose of fentanyl is an alternative. Isoprenaline is often used to provoke dysrhythmia, and adenosine may be given to help identify an aberrant pathway. Adenosine may induce bronchospasm and should be avoided in children with asthma. Dexamethasone as antiemetic prophylaxis should be avoided in these patients, as its anti-inflammatory effect may ameliorate the 'burn' and compromise the ablation. The procedures can be prolonged; appropriate methods to monitor and maintain temperature should be used.

Implantation of Pacemakers and Other Devices

Some permanent pacemakers are implanted in the catheter laboratory, usually in the left subclavicular region, with transvenous pacing leads inserted into the subclavian vein. Where the nature of an intermittent dysrhythmia cannot be identified, an indwelling ECG loop recorder may be implanted in the subclavicular or parasternal area. Anaesthesia is generally straightforward and

should include intravenous and topical analgesia, together with prophylactic antibiotics.

Implantable Cardioverter Defibrillator (ICD)

Several disorders are associated with sudden death in childhood due to an arrhythmia which may be prevented by an ICD. These include:

- Hypertrophic obstructive cardiomyopathy (HOCM)
- Catecholaminergic polymorphic ventricular tachycardia (CPVT)
- Arrhythmogenic right-ventricular cardiomyopathy (ARVC)
- Long QT syndrome
- Brugada syndrome

Many of these patients will have experienced a life-threatening arrhythmia or have a family history of sudden cardiac death. The procedure requires the placement of ventricular pacing leads via the subclavian vein and ICD device insertion in the subclavicular or axillary area. The device is designed to detect ventricular tachycardia or fibrillation and deliver an electrical shock to cardiovert. It will also pace where necessary. Once inserted, it is necessary to test that it is working satisfactorily by inducing ventricular fibrillation. Resuscitation drugs should be on hand, and external defibrillation pads should be placed in case the device does not function as intended. Inducing ventricular fibrillation can lead to severe cardiac decompensation in some patients, such as those with severe cardiomyopathy, and invasive arterial pressure monitoring and central venous access should be used.

Induction of anaesthesia can be challenging in patients with severe HOCM, particularly those with significant left-ventricular outflow tract obstruction (LVOTO), exacerbated by systolic anterior motion (SAM) of the mitral valve and with diastolic dysfunction. The LVOTO is dynamic, and it is important to avoid increased sympathetic activity that may increase it. Adequate ventricular filling is essential, so maintaining good hydration preoperatively, for example with intravenous fluids, and avoiding tachycardia are important. These patients will often be on β-blockers, which should not be stopped, and anxiolytic premedication is recommended. For induction a combination of fentanyl 1–2 mcg kg^{-1}, slow incremental doses of midazolam 50 mcg kg^{-1} over a few minutes, and a small dose of propofol works well. Sevoflurane can be used where intravenous induction is not appropriate.

Lead Extraction

The need for pacing or an ICD is usually a lifelong burden. The battery of an implanted device is limited. Battery-depleted pulse generators can be replaced so long as the implanted endovenous leads are working as planned (threshold, capture, etc.). Growth of a child, or simply the passage of time, may cause dysfunction of pacing leads and indicate replacement. Under such circumstances, there may be an indication to extract old pacing leads, to allow space within the vessel for the new leads. These procedures may be difficult when the leads have been in for an extended period because they can become tethered or encased in fibrous or calcified tissue. Various modalities and specialised procedures (telescoping sheaths, laser sheaths, rotational mechanical cutters) may be employed to separate leads from tethering tissue and can be prolonged and dangerous with risk of laceration of the major vein (SVC or brachiocephalic vein). A surgical team must be on standby and be prepared to repair catastrophic injury. Whilst mobilising the surgical team, it may be necessary to tamponade a lacerated vessel by gently inflating a large balloon in the vein. Major haemorrhage protocols must be in place, including rapid infusion equipment. Unusual surgical approaches to access the vessel may be necessary (e.g. division of the clavicle). Another risk of lead extraction is lead fracture and embolisation of fragments of the lead, which may involve more specialised catheter techniques for retrieval.

Pericardial Effusion Drainage

Insertion of a pericardial needle or drain to relieve a pericardial effusion is usually performed under echocardiographic guidance. General anaesthesia can be challenging as these patients may have a severely compromised circulation from cardiac tamponade, rendering them highly preload dependent. Positive pressure ventilation reduces preload and so is avoided if possible. Ketamine is often advocated as an induction agent as it allows spontaneous ventilation to be maintained whilst maintaining myocardial contractility and SVR.

Profound hypotension can occur when the effusion is drained as the heart becomes acutely underfilled, and it is important that the effusion is drained slowly. Adequate venous access for rapid volume administration is essential. The situation is not helped by the need for the patient to be semi-erect to facilitate the effusion gravitating to the base of the heart. In adolescents, it may be safer to undertake this under local anaesthesia if possible.

Cardiac MRI and CT

Cardiac MRI and magnetic resonance angiography (MRA) are increasingly used in the diagnosis and assessment of congenital heart disease, particularly for demonstrating 3D anatomical relationships and quantifying blood flows. It has the advantage that there is no radiation, although there is the need for MRI-compatible equipment and a general anaesthetic, as the scans are long. There is generally a need for short periods of apnoea, so controlled ventilation is required.

Many cardiac CT scans are very quick and can often be undertaken with sedation, or in small infants with appropriate swaddling. General anaesthesia may be needed for CT angiography, as a cannula will be needed for the contrast, and a short breath-hold may be required. CT coronary angiography requires a heart rate of around 80 bpm; dexmedetomidine is useful in achieving this.

These investigations are often undertaken to plan further surgical procedures in patients reliant upon a systemic to pulmonary shunt and who may be polycythaemic. It is vitally important to avoid dehydration, and clear oral fluids should be maintained until one hour before the procedure (or two hours if known reflux). Where this is not possible, intravenous fluids should be administered before anaesthesia.

Further Reading

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