Vascular access and monitoring

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Introduction

Hemodynamic assessment and treatment through invasive access to the circulation is crucial for every patient undergoing surgery for congenital cardiac disease. Secure, reliable venous and arterial access is necessary for accurate beat-to-beat monitoring of pressures and waveforms, and frequent sampling for blood gases, hematocrit, coagulation studies, and metabolic parameters. In this manner, pathophysiologic processes associated with the patient’s underlying disease or the surgical procedure can be detected and treated as early as possible, with the goal of lessening morbidity. Central venous access is critical to directly infuse vasoactive medications and to deliver bolus drugs to achieve the desired hemodynamic effects in as short a time as possible. Large bore peripheral venous access is important to infuse crystalloids, colloids, and blood products with minimal resistance to flow. All of these procedures may be technically difficult, time consuming, and have significant morbidity, especially in newborns or small infants who comprise an increasingly large portion of the patients presenting for surgery. Meticulous attention to the details of vascular access by the pediatric cardiac anesthesiologist can maximize the benefits and minimize the risks to the patient. This chapter will review the techniques of vascular access in congenital cardiac surgery patients, emphasizing newer imaging modalities to guide successful placement, and strategies to avoid complications.

Venous access

Peripheral veins

Any visible peripheral vein, and many that are not visible, may be utilized for peripheral venous access. One strategy in pediatric cardiac patients is to cannulate a small superficial vein on the hand or foot with a small catheter (24 or 22 gauge) before induction, or during inhalation induction of anesthesia to facilitate the early administration of muscle relaxants and provide expeditious airway management. Later, with the airway secure and with an immobile patient, larger bore peripheral venous access can be achieved. Recommended sizes are 22-gauge 1” (25.4 mm) catheters for infants newborn through 6 months, 20-gauge 1.25” catheters for 6 months to 3 years, 18-gauge 1.5” for 3–12 years, and 16 or 14-gauge 2” catheters for teenage or adult patients. Resistance to fluid flow predicted by Pousielle’s law is proportional to the length of the catheter and the viscosity of the fluid, and inversely proportional to the fourth power of the catheter radius. When rapidly infusing the more viscous colloids or packed red blood cells, it is important to use a large bore, short catheter in a large peripheral vein. Central venous catheters (CVCs) are usually less desirable for this use due to their smaller lumens and much longer lengths.

Any unusual resistance to infusion through a peripheral intravenous catheter must be immediately investigated. If the catheter is inaccessible, immediately change to a functioning catheter to avoid extravasation. Caustic or vasoactive substances, e.g. calcium chloride, dopamine, epinephrine, etc., should not be injected through peripheral veins unless no other alternative exists because of the risk of extravasation and tissue necrosis—such drugs should all be injected centrally.

The saphenous vein at the ankle is large and in a constant anatomic position in patients of all ages. It can usually be cannulated even if it cannot be seen or palpated. A recommended technique is to apply a tourniquet below the knee, prepare the site antiseptically, and extend the ankle at the medial malleolus with one hand while puncturing the skin at a shallow angle of 10–30° with an angiocatheter 0.5–1.0 cm lateral and about 1 cm inferior to the medial malleolus. Advance the catheter slowly in the groove between the malleolus and the tibialis tendon until blood return through the needle is established. Advance the needle and catheter together several millimeters, then advance the catheter over the needle into the vein with the index finger of the same hand that made the skin puncture, while maintaining extension of the ankle so that the saphenous vein is tethered straight.
in its course, to minimize the possibility of puncturing the vein wall due to kinking of the vein. If the vein can be entered but the catheter will not advance its full length into the vein, a small flexible guidewire of 0.015″ (0.381 mm) or 0.018″ (0.457 mm) may be used to assist in cannulation of the saphenous or any other peripheral vein.¹

Other large peripheral veins may be found in infants and children on the dorsum of the hand, at the wrist superficial to the radial head, as branches of the cephalic or brachial venous system in the antecubital fossa, or on the dorsolateral aspect of the foot. The latter site is especially prominent in many newborns. The principles of the techniques of cannulation are the same as for the saphenous vein, emphasizing extension of the underlying extremity, slow careful cannulation with one hand, and the use of a small guidewire if necessary. Multiple attempts may be required for veins that are not visible or palpable. Often, very small adjustments in direction or depth of cannulation attempts of a millimeter or less result in successful cannulation. It is sometimes necessary to attempt cannulation of several sites, and occasionally it is not possible to obtain peripheral access due to previous indwelling peripheral catheters in chronically ill children.

The external jugular vein is almost always visible in infants and children undergoing cardiac surgery, and is often enlarged and easily cannulated due to elevated right heart pressures. A recommended technique is to choose the larger external jugular vein, place a small rolled towel under the shoulders and place the patient in 30° Trendelenberg position, prepare the site antiseptically, and have an assistant compress the vein gently with pressure just above the clavicle to further distend it. Rotation of the head 45–90° away from the side of cannulation, and slight extension of the neck and traction of the skin over the vein with one hand will tether the vein into a straighter course to facilitate successful cannulation. The vein is punctured high in its visible course with an angiocatheter attached to a syringe filled with heparinized saline, and with the needle bent upwards 10–20° to facilitate the very flat, superficial angle of incidence necessary to cannulate the vein without puncturing its back wall. With constant, gentle aspiration of the syringe, the vein is entered and catheter advanced into the vein. Short peripheral catheters of the same size as recommended above should be used. A catheter advanced too far into the venous plexus beneath the clavicle will often exhibit resistance to the free, gravity driven, flow of fluid, and traction or withdrawal of the catheter a few millimeters may be necessary. External jugular catheters are often difficult to secure to the skin on the neck, and suturing them in place is recommended. This will enhance stability postoperatively as the patient begins moving. One advantage of using the external jugular vein for a peripheral venous catheter is that it is easily accessible under the surgical drapes, and can be frequently monitored for extravasation or kinking of the catheter, which is more common with this site than with the other commonly used peripheral veins.

**Intraosseous access**

Intraosseous access to the venous circulation has been described for use during a crisis when no other venous access is available, e.g. during cardiopulmonary resuscitation or shock.² Rarely, it may be required for emergency resuscitation in the cardiac operating room, and therefore it is necessary for the pediatric cardiovascular anesthesiologist to be familiar with the technique. Normally this procedure is used only in small children, and the flat surface of the proximal tibia is used. Commercially available 14- or 16-gauge intraosseous needles, or 16-gauge bone marrow aspiration needles may be used. The site is aseptically prepared, the skin is punctured and the outer bony cortex is contacted. With a boring motion, the needle is advanced through the outer cortex into the marrow space, heralded by a sudden loss of resistance. Infants have active marrow production in long bones, and when the stylet is removed and the needle aspirated bone marrow should appear in the hub. Rapid infusion of 10 ml normal saline without extravasation confirms proper placement, and emergency drugs and fluids may be administered. They reach the central circulation via the bone marrow sinusoids, which connect to the emissary veins from the bony cortex, and then to the larger veins draining into the central circulation. Drugs injected intraosseously, e.g. epinephrine, reach the heart slightly more slowly than when injected into a central vein, but the peak drug levels are not different.² Intraosseous needles should be available for the rare crisis in the operating room or intensive care unit (ICU). Intraosseous needles should be replaced as soon as possible with conventional peripheral or central venous access.

**Central venous access**

**Umbilical vein**

The umbilical vein in the fetus is a conduit to carry oxygenated and detoxified blood from the placenta, through the abdominal wall, through the liver and patent ductus venosus to the inferior vena cava (IVC) and the right atrium (RA) (Fig. 7.1).³ This vessel can usually be cannulated at the umbilical stump for the first 3–5 days of postnatal life. Passage into the IVC depends on the patency of the ductus venosus, which often exists for the first few days, just as the ductus arteriosus. Sterile technique without a guidewire is used to pass the catheter blindly a premeasured distance. If no resistance to passage is met and free blood return is achieved, the catheter tip is usually in the high IVC or RA, and functions as a CVC. Catheter tip position must be determined by radiography as soon as possible to determine if it is through the ductus venosus into the IVC or the RA. Often, the ductus venosus is not patent, and the catheter tip passes into branches of the hepatic veins, and is visible in the liver radiographically. In this location the catheter must not be used except for
not be exposed to the risk of thrombosis and permanent occlusion. This complication in the neonate carries a high rate of morbidity and mortality (see below). Umbilical venous catheter cannulation is especially important for patients with planned multiple interventions such as single-ventricle patients, who often require at least two cardiac catheterizations and two additional surgeries. A UVC can be left in place for as long as 14 days if no complications are suspected. When the umbilical vein is utilized, transthoracic right atrial catheters with their attendant risks of bleeding and pericardial or pleural effusions may not be necessary.

**Percutaneous central venous access**

Percutaneous central venous access is the standard approach in many cardiac surgery programs. The author recommends using a double lumen central line of the smallest acceptable size for percutaneous CVC placement. For all sites, either audio Doppler or two-dimensional ultrasound is used to facilitate insertion (see discussion below). The larger distal lumen is used for CVP monitoring and drug injection, and the smaller proximal lumen for vasoactive infusions. The smallest available double lumen catheter is currently 4 Fr in size. Superior vena cava (SVC) catheters should be used with caution or not at all in patients weighing less than 4 kg because of the increased risk of thrombosis (see Complications of vascular access section below). Recommended sizes and lengths are shown in Table 7.1.

Sterile technique using gown and wide draping leads to a “cleaner” insertion technique with fewer infectious complications. In cardiac patients, the left side SVC lines should generally be avoided. The risk of erosion/perforation is greater (see below), and 5–15% of patients with congenital cardiac disease have a persistent left SVC, which most often drains either to the coronary sinus or left atrium, neither of which is a desirable location for a catheter tip. So, if left-sided line placement is contemplated, ascertain by echocardiography or cardiac catheterization report the presence of left SVC. If this is not known, choose an alternate site, i.e. femoral or intracardiac (see below).

The following general discussion of the Seldinger technique in pediatric patients can be applied to all percutaneous vascular access sites, either venous or arterial. The Seldinger
monitoring

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heel of the non-dominant hand, while threading dilators, with direct compression of bleeding puncture sites using the blood loss in small infants during catheterization procedures, vascular insufficiency. Meticulous attention must be paid to which may lead to an increased incidence of thrombosis or minimize bleeding and trauma to the vessel wall, both of preferable to make the smallest possible hole in the vein to

for small infants, and either passage of the catheter without i.e. 5-Fr dilator for 4-Fr catheter. This may be undesirable packaged CVC kits are often one size larger than the catheter, and catheter passage follows. The dilators in the pre-

incision with a no. 11 scalpel is made. Finally, careful dilation of only 1 mm or less may be enough to prevent passage of the guidewire. It is very important to have the guidewire prepared to insert and immediately accessible when the vein is entered, so the anesthesiologist does not have to look away from the puncture site to reach for the wire on a distant tray, often resulting in enough movement of the needle to prevent successful guidewire passage. After the desired vein is entered, the needle position is fixed by stabilizing it against the patient’s body with the heel of the non-dominant hand, and the guidewire is carefully advanced into the RA. The resistance to wire passage should be minimal. Experienced operators learn to recognize the “feel” of a guidewire passing successfully. If any resistance is encountered, the wire must be carefully withdrawn, and another approach made if the needle is still in the vessel, ascertained by free aspiration of blood. Forcing a guidewire in the face of resistance can lead to significant complications. The electrocardiogram (ECG) should be carefully observed as the guidewire is slowly advanced. Premature atrial contractions (PACs) are usually observed as the first guidewire-induced dysrhythmia, signifying atrial location. If no PACs are observed, the operator should suspect that the guidewire is not in the atrium. If ventricular extrasystoles are the first observed dysrhythmia, especially if they are multifocal in nature, the wire is very likely in an artery, and the left ventricle has been entered retrograde. The wire must be withdrawn immediately, or the position ascertained by imaging, e.g. transesophageal echocardiography (TEE). In difficult or questionable cases TEE may be utilized to visualize the guidewire, and this is strongly recommended before the passage of a vessel dilator or the catheter. After guidewire passage, a very small skin incision with a no. 11 scalpel is made. Finally, careful dilation and catheter passage follows. The dilators in the pre-packaged CVC kits are often one size larger than the catheter, i.e. 5-Fr dilator for 4-Fr catheter. This may be undesirable for small infants, and either passage of the catheter without dilation, or use of a dilator the same size as the catheter is preferable to make the smallest possible hole in the vein to minimize bleeding and trauma to the vessel wall, both of which may lead to an increased incidence of thrombosis or vascular insufficiency. Meticulous attention must be paid to blood loss in small infants during catheterization procedures, with direct compression of bleeding puncture sites using the heel of the non-dominant hand, while threading dilators, catheters, etc. Use of an assistant may be necessary in difficult catheterizations. After passage of the catheter to the desired depth, it is secured with sutures and a dressing. If more than 1 cm of catheter is outside the patient, additional suturing or catheter holding devices are necessary.

Internal jugular vein

The right internal jugular (IJ) vein is the most common site chosen for central venous access in pediatric cardiac surgery. It is large, and runs in close proximity superficial to the carotid artery along most of its length. The primary advantage of using the IJ vein is that it provides a direct route to RA, and thus a high rate of optimal catheter positioning if the vessel can be cannulated. Various studies report only a 0–2% incidence of catheter tip outside the thorax, in contrast to the subclavian route (see below). The primary disadvantage comes from difficulty in cannulation in small infants, who have large heads and short necks, and thus there is difficulty in obtaining the shallow angle of approach necessary to access the vessel. Also some series report a 10–15% incidence of carotid artery puncture in infants and ultrasound studies of neck vessel anatomy reveal the partial or complete overlap of the IJ vein anterior to the carotid artery.9,10 This site is also not comfortable for some awake infants, and tip migration may be significant with turning the head or flexion/extension of the neck.11 All insertion techniques involve placing a small roll under the shoulders, using steep Trendelenberg position, and rotating the head no more than 45° to the left—greater rotation will produce more overlap of the IJ vein and carotid artery, and increase the risk of carotid puncture.12 Recent studies have demonstrated that liver compression and simulated valsava maneuver also increase the diameter of the IJ vein, possibly increasing the success rate of cannulation.13

There are numerous approaches to the IJ vein, some of which are described here (Fig. 7.2):
1. Muscular “triangle” method: puncture at the top of the junction where the sternum and clavicular heads of the sternomastoid muscle meet, lateral to the carotid impulse, directing the needle at the ipsilateral nipple. These landmarks are often not well defined in infants.
2. Puncture exactly halfway along a line between the mastoid process and the sternum, just lateral to the carotid impulse.
3. Use the cricoid ring as a landmark, and puncture just lateral to the carotid impulse.
4. Jugular notch technique: puncture just lateral to the carotid impulse, just above the jugular notch on the medial clavicle—a low approach.

An ultrasound technique (see below) should be used to clearly identify the course of the vessel and to detect any significant overlap with the carotid artery. There is no need to use a finder needle for small catheters where the access needle is 20 gauge or smaller. Surface landmarks are often inaccurate for estimating the correct depth of insertion for SVC lines, i.e. locating the tip midway between the sternal
The right subclavian vein should always be the first choice (see below). Turn the head toward the side being punctured (i.e. toward right for the right-sided line). This position will compress the IJ vein on that side and prevent the guidewire from entering it, especially in infants, which may lead to complications such as dural sinus thrombosis. It will not, however, prevent the guidewire from crossing the midline and entering the contralateral brachiocephalic vein. The needle is bent upwards in mid-shaft at a 10–20° angle to assure a very shallow course. In the author’s experience the puncture site that is most successful is 1–2 cm lateral to the midpoint of the clavicle, directly lateral from the sternal notch, with the needle directed at the sternal notch. Contact the clavicle first to assure a shallow angle of incidence to minimize the risk of pneumothorax. Then, the needle is “walked” carefully underneath the clavicle and advanced slowly with constant aspiration until blood return is achieved. Advancing the needle only during expiration is recommended to minimize the risk of pneumothorax. Having an assistant manually ventilate the patient will facilitate this process. If not successful, the needle is withdrawn slowly with gentle aspiration, because about 50% of infant subclavian veins are cannulated during withdrawal due to compression or kinking of the vein during needle advancement. Slow, controlled, careful needle manipulation, especially in small infants, must be emphasized.

After the vein is entered, advance the guidewire there should be no resistance. Look for PACs, sometimes only one or two, as a sign that the wire is in the heart. If no dysrythmias are seen, withdraw the wire, rotate it 90° clockwise, and advance it again until PACs are seen. Use a dilator (be very careful not to advance it too far—only far enough to expand the space between the clavicle and first rib) and pass the catheter to the desired depth using the one of the guidelines noted below.

Complications during subclavian catheterization occur when a needle angle of incidence is too cephalad, resulting in arterial puncture, or too posterior, resulting in pneumothorax. If the needle course remains shallow, just underneath the clavicle, and directed straight horizontally at the sternal notch, complications are rare. Advancing the needle too far in infants may result in puncture of the trachea.

External jugular vein
Advantages of this approach are its superficial location and thus low risk of arterial puncture. The disadvantage is that the younger the patient, the less likely it is that the guidewire will pass into the atrium; the success rate is less than 50% if the patient is less than 1 year of age, and only 59% in patients less than 5 years of age. Positioning is the same as the IJ approach, the vein is punctured high in its course, and the guidewire is passed. Often it can be observed turning medially toward the SVC. If no resistance is felt, and PACs are seen, or the guidewire is visualized on the TEE, then passage has been successful. Because of the low success rate of central

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**Fig. 7.2** Sites for central venous cannulation of the superior vena cava (SVC). (1) High approach, midway between mastoid process and sternal notch. (2,3) Middle approach using apex of muscular triangle or cricoid cartilage. (4) Low approach using jugular notch. (5) Lateral approach to subclavian venipuncture. RA, right atrial. Reproduced with permission from Andropoulos DB, Bent ST, Skjonsby B, Stayer SA. The optimal length of insertion of central venous catheters for pediatric patients. *Anesth Analg* 2001; 93: 883–6.
cannulation from the external jugular vein approach, our practice is to use the IJ vein first in all patients.

**Femoral vein**

The femoral vein has long been used for central venous catheterization in pediatric patients, with no greater infection or other complication rate compared to other sites. This is the site of choice for single ventricle patients through the first 6 months of life, because of the increased thrombosis risk in this population. A successful cavopulmonary connection will depend on a patent SVC circulation to provide over half of their pulmonary blood flow. Thus, SVC thrombosis will lead to inadequate drainage from the upper half of the body to the pulmonary circulation and cause SVC syndrome.

The left side is preferred because it avoids the cardiologists’ favorite site, the right femoral vein. The single ventricle patient will receive multiple interventions, e.g. catheterizations and surgeries, so preserving vascular patency is extremely important.

**Technique**

The patient is positioned with a rolled towel under the hips for moderate extension. The puncture site should be 1–2 cm inferior to the inguinal ligament (line from the anterior superior iliac spine to the symphysis pubis), and 0.5–1.0 cm medial to the femoral artery impulse, with the needle directed at the umbilicus. Ultrasound guidance is important for the greatest chance for first pass, atraumatic placement. The guidewire is passed, ensuring no resistance. A vessel dilator is used, then the catheter is passed all the way to the hub to position the tip in the mid-IVC. It is important to puncture the vessel well below the inguinal ligament, to minimize the risk of unrecognized retroperitoneal bleeding. Bleeding below the inguinal ligament is easily recognized and treated with direct pressure.

Several studies have conclusively demonstrated that in the absence of increased intra-abdominal pressure or IVC obstruction, mean CVP as measured in the IVC below the diaphragm is identical to that measured in the RA in patients with and without congenital heart disease. The only caveat is in the patient with interrupted IVC with agenesis of the inferior vena cava and right atrial pressures where these conditions has not been evaluated, but the catheter can be used as any other central line for infusion of drugs and fluids.

**Direct transthoracic intracardiac vascular access**

These are catheters placed by the surgeon directly into the right or left atrial appendages or upper pulmonary vein and threaded into the left atrium, secured by a pursestring suture. Pulmonary artery (PA) catheters are placed high in the right ventricular outflow tract, through the pulmonary valve, or into the main PA. Some institutions employ continuous mixed venous oxygen saturation monitoring with PA catheters. Transthoracic catheters are usually placed during rewarming on cardiopulmonary bypass. They may be used for pressure monitoring or vasoactive drug infusion. Advantages of this approach include saving time before bypass because percutaneous central lines are not placed, tip location is assured by direct vision, and vessel injury from percutaneous catheters is avoided. Disadvantages are that no central access is available before bypass, which may be important for unstable patients, and there is a low risk of cardiac tamponade when these catheters are removed. For this reason many institutions do not remove the mediastinal drainage tube postoperatively until the intracardiac lines are removed, or wait 3–5 days, to minimize the risk of bleeding. This either limits the lifespan of these lines and may leave the patient without adequate venous access, or may delay discharge from the ICU or hospital while waiting to remove these catheters.

A left atrial catheter is frequently utilized when a degree of postoperative left ventricular dysfunction is anticipated, as in complex newborn surgery such as the arterial switch operation, or after mitral valve surgery. Pulmonary artery catheters are utilized in the face of known significant preoperative and anticipated postoperative pulmonary hypertension, i.e. obstructed total anomalous pulmonary venous return, some complete atrioventricular canal patients, or patients with severe mitral valve disease.

In the largest series reported detailing the use and complications of transthoracic catheters, there was overall a 0.6% incidence of serious complications, defined as significant bleeding or catheter retention out of 6690 transthoracic catheters. This risk was greatest for PA catheters (1.07% with three severe cardiac tamponades and one death out of 1680 catheters), followed by left atrial catheters, then right atrial catheters. More recent reports give similar results, documenting a higher risk of bleeding with platelet counts of less than 50 000/L, and a 0.6% incidence of atrial thrombus in a study of 523 transthoracic catheters. To date there are no outcome studies comparing transthoracic and percutaneous catheters.

**Continuous superior vena cava oxygen saturation monitoring after the Norwood operation for hypoplastic left heart syndrome**

Continuous monitoring of mixed venous saturation (SvO₂) in the SVC using near-infrared oximetric catheters has recently been demonstrated to be very useful in post-bypass management of neonates undergoing the Norwood operation for hypoplastic left heart syndrome. Therapy is directed at maintaining SvO₂ at 50% or greater, and when this goal is achieved as part of an overall management strategy, 30 day survival has been greater than 95% in recent reports. SvO₂ less
than 30% confers a significant risk of anaerobic metabolism and increased risk for poor outcome.

These catheters are placed by the surgeon transthoracically during rewarming, a short distance into the SVC. They remain in place for 2–5 days, and are removed exactly like other transthoracic catheters. Complication rate, e.g. bleeding or thrombosis, has been zero in the series reported thus far.

**Transesophageal echocardiography**

Transesophageal echocardiography is used for many congenital heart operations. Catheter tips and guidewires are easily imaged with TEE (Fig. 7.4), and one recent study using TEE-guided CVC placement demonstrated a 100% success rate for correct placement in the SVC when TEE was used, vs. 86% when surface anatomical landmarks were used in infants and children undergoing congenital heart surgery.¹⁸

The TEE probe is placed before CVC attempts are made, and the SVC–right atrial junction in the 90° plane is imaged. When the vessel is punctured and the guidewire passed, it should be visualized passing from the SVC into the RA. Then the catheter is passed to its full length, the guidewire removed, and the tip of the CVC identified. Flushing the CVC with saline creates an easily visible stream of contrast which identifies the tip. The CVC is then pulled back until it is above the RA, in the distal SVC 1–2 cm above the crista terminalis. Using this technique, immediate, accurate confirmation of placement is obtained before final securing, and before the surgery. The proximal SVC, which is more than 2 cm above the RA, is difficult to image using TEE, so this method is most accurate in placing CVC in the distal SVC. Also, the commonly accepted radiographic SVC–RA junction is often higher than the SVC–RA junction noted by TEE.¹⁸

**Electrocardiographically-guided placement**

The intravascular ECG may be used in children to guide correct CVC placement.³³,³⁶,³⁷ Either a 0.9% or 3% saline-filled lumen with special ECG adaptor, or a guidewire within the lumen attached to a sterile alligator clip and leadwire substituted for the right arm surface ECG lead may be used. Entry
of the catheter tip into the RA is signified by the sudden appearance of a P atriale, an exaggerated, large, upright P wave. The catheter tip is then pulled back 1–2 cm into the desired position in the SVC. Success rate for proper placement in the reported studies has been 80–90%, but there have been no controlled studies in children comparing this method to other methods. This method also requires special equipment not always available.

Height- and weight-based formulae

A recent large study of CVC placement in infants and children undergoing congenital heart surgery developed formulae for correct insertion depth based on height and weight (Table 7.2).38 Central venous catheters were inserted in the right IJ or subclavian vein and the postoperative radiograph studies were used to determine the tip position in reference to the SVC–RA junction. The length of catheter inside the patient was added to this distance to determine the position of the SVC–RA junction, and formulae developed that would predict placement above the RA, in the SVC 97.5% of the time (95% confidence interval 96–99%). All catheter tips predicted to be in the atrium using this data would be high in the RA within 1 cm of the SVC–RA junction, minimizing any perforation risk. The formulae are simple and easily implemented because weight and height are known on all patients undergoing cardiac surgery.

For patients with height less than 100 cm: (Height ÷ 10)–1 cm is the correct insertion distance (i.e. a 75-cm patient would have the catheter secured at 6.5 cm for either the IJ or the subclavian route).

<table>
<thead>
<tr>
<th>Patient weight (kg)</th>
<th>Length of CVC insertion (cm)</th>
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<tbody>
<tr>
<td>2.0–2.9</td>
<td>4</td>
</tr>
<tr>
<td>3.0–4.9</td>
<td>5</td>
</tr>
<tr>
<td>5.0–6.9</td>
<td>6</td>
</tr>
<tr>
<td>7.0–9.9</td>
<td>7</td>
</tr>
<tr>
<td>10.0–12.9</td>
<td>8</td>
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<tr>
<td>13.0–19.9</td>
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</tr>
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<td>20.0–29.9</td>
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<td>40.0–49.9</td>
<td>12</td>
</tr>
<tr>
<td>50.0–59.9</td>
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<tr>
<td>60.0–69.9</td>
<td>14</td>
</tr>
<tr>
<td>70.0–79.9</td>
<td>15</td>
</tr>
<tr>
<td>80 and above</td>
<td>16</td>
</tr>
</tbody>
</table>

For patients with height 100 cm or greater: (Height ÷ 10)–2 cm is the correct distance.

The caveats to this seemingly useful technique are that for the IJ vein, the puncture site was high, exactly midway between the mastoid process and the sternal notch; and for the subclavian, a puncture site 1–2 cm lateral to the midpoint of the clavicle. If different puncture sites are utilized, the operator must adjust the formulae accordingly. Also, the formulae have not yet been evaluated for accuracy in a prospective fashion.
Percutaneously inserted central catheters

Percutaneously inserted central catheters (PICCs) have been utilized in the neonatal nursery for more than a decade, and have become standard practice for ill newborns expected to require prolonged venous access. The complication rate for these catheters is very low, and they are usually relatively easy to insert into the central circulation via the antecubital, saphenous, scalp, hand, axillary, or wrist veins, when placed by experienced, skilled personnel. Such personnel include nurses or physicians placing them at the bedside, or in the interventional radiology suite with ultrasound and fluoroscopic guidance. The key to successful placement is early access, before all large visible superficial veins are injured from attempts at peripheral intravenous placements. For this reason, the PICC line is optimally placed in the critically ill newborn with congenital heart disease in the first 12–24 hours after admission. Like all CVCs they occasionally cause complications such as perforation of the atrium, or embolization of a portion of the catheter. The infection rate is very low.

Technique

A suitable vein should be identified. The branches of the basilic vein on the medial half of the antecubital fossa offer the highest success rate because of the large size and direct continuation with the axillary and subclavian veins. The cephalic vein tributaries can also be used, but are less likely to pass into the axillary vein. Other sites, e.g. the saphenous, hand, and scalp veins are cannulated as for a peripheral intravenous catheter. The site is prepared and draped, and appropriate local anesthesia and/or intravenous analgesia are administered. The vein is entered using a large breakaway needle or angiocatheter, and a 2-Fr non-styled silicone catheter flushed with heparinized saline is passed with forceps a distance measured from the entry site to the SVC–RA junction. Continued easy passage without resistance and identification of the vessel. Puncture of the artery should optimize conditions, e.g. positioning, lightening, and identification of the vessel. Puncture of the artery with the needle is signified by brisk flashback. The needle and catheter are then advanced 1–2 mm into the artery, and an attempt is made to thread the catheter primarily over the needle its full length into the artery. Threading should have minimal resistance and is signified by the continuing flow of blood into hub of needle. If threading is not successful, the

### Table 7.3 Recommended arterial catheter sizes: radial, dorsalis pedis (DP), posterior tibial (PT), and brachial arteries.

<table>
<thead>
<tr>
<th>Weight</th>
<th>Radial/DP/PT arteries</th>
<th>Brachial artery</th>
</tr>
</thead>
<tbody>
<tr>
<td>&lt; 2 kg</td>
<td>24 g</td>
<td>Not recommended</td>
</tr>
<tr>
<td>2–5 kg</td>
<td>22 g</td>
<td>24 g</td>
</tr>
<tr>
<td>5–30 kg</td>
<td>22 g</td>
<td>22 g</td>
</tr>
<tr>
<td>&gt; 30 kg</td>
<td>20 g</td>
<td>22 g</td>
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### Table 7.4 Recommended arterial catheter sizes: femoral and axillary arteries.

<table>
<thead>
<tr>
<th>Weight</th>
<th>Femoral/axillary arteries</th>
</tr>
</thead>
<tbody>
<tr>
<td>&lt; 10 kg</td>
<td>2.5 Fr, 5 cm long</td>
</tr>
<tr>
<td>10–50 kg</td>
<td>3 Fr, 8 cm long</td>
</tr>
<tr>
<td>&gt; 50 kg</td>
<td>4 Fr, 12 cm long</td>
</tr>
</tbody>
</table>

### Arterial access

Tables 7.3 and 7.4 display recommended catheter sizes for arterial access based on site and patient weight.

### Radial artery

This is the preferred location in the newborn if an umbilical artery line is not possible or needs to be replaced, and in virtually all other patients. Placement on the same side of an existing or planned systemic to PA shunt is avoided, e.g. a right-sided modified Blalock–Taussig shunt.

**Technique**

The wrist is extended slightly with rolled gauze, the fingers taped loosely to an armboard, with the thumb taped separately in extension to tether the skin surface over the radial artery. An angiocatheter flushed with heparinized saline is used to increase the rapidity of flashback of blood into the hub of the needle after aseptic preparation. The skin is punctured at a 15–20° angle at the proximal wrist crease at the point of maximal impulse of the artery. Palpation is the usual method of identifying the artery, but audio Doppler localization can be helpful if the pulse is weak. Lighter planes of anesthesia provide stronger pulses and increase the success rate of cannulation. The first attempt, before any hematoma formation, always yields the greatest chance for success, so the operator should optimize conditions, e.g. positioning, lighting, and identification of the vessel. Puncture of the artery with the needle is signified by brisk flashback. The needle and catheter are then advanced 1–2 mm into the artery, and an attempt is made to thread the catheter primarily over the needle its full length into the artery. Threading should have minimal resistance and is signified by the continuing flow of blood into hub of needle. If threading is not successful, the
needle is replaced carefully in the angiocatheter, and the needle and catheter can be passed through the back wall of artery. Then the needle is removed, and a 0.015″ guidewire with flexible tip can be used to assist threading of catheter. The catheter is pulled back very slowly, and when vigorous arterial back flow occurs, the guidewire is passed, and the catheter threaded over the guidewire into the artery. Minimal resistance signifies successful threading. If unsuccessful, further attempts may be made at the same site, or at slightly more proximal sites to avoid areas of arterial spasm, thrombosis, or dissection. The circulation distal to the catheter should be assessed by inspection of color and capillary refill time of fingertips and nailbeds, and quality of signal from a pulse oximeter probe. A recommended technique for securing the catheter is with a clear adhesive dressing and transparent tape so that the insertion site and hub of the catheter are visible at all times.

**Femoral artery**

The superficial femoral artery is a large vessel that is easily accessible in almost all patients,43 and is a logical second choice when radial arterial access is not available. In infants, especially patients with trisomy 21, transient arterial insufficiency develops in up to 25% of patients after arterial catheterization when 20-gauge (3-Fr) catheters are used.43 For this reason, in the author’s institution, the smallest commercially available catheter, 2.5 Fr (equal to 21 gauge), is used in patients weighing less than 10 kg (see Table 7.4).

**Technique**

A small towel is placed under the patient’s hips to extend the leg slightly to a neutral position. Slight external rotation, with the knees restrained by taping to the operating room bed fixes adequate position. After sterile preparation and draping, the course of the superficial femoral artery is palpated and punctured 1–2 cm inferior to the inguinal ligament, to avoid puncturing the artery above the pelvic brim, where a retroperitoneal hematoma could develop. If the pulse is weak, as in the case of aortic arch obstruction, use of audio Doppler effectively identifies the course of the vessel. The puncture technique varies, and may include direct puncture with an angiocatheter, or Seldinger technique using the needle in the commercially supplied kit, or a 21-gauge butterfly needle with the extension tubing removed. All of these are flushed with heparinized normal saline to increase the rapidity of flashback. A small flexible guidewire, 0.015″ (0.381 mm) or 0.018 (0.457 mm)″, is used. It is normally possible to thread a polyethylene catheter over the guidewire without making a skin incision, and under no circumstances is dilating the tract and artery with a dilator recommended, which could cause arterial spasm, dissection, or bleeding around the catheter if the puncture site is large. The catheter is secured by suturing around the entry site of catheter and wings around the hub.

Distal perfusion is immediately assessed, and a pulse oximeter probe is placed on the foot for continuous monitoring and early warning of arterial perfusion problems.

**Brachial artery**

The brachial artery has been successfully used for monitoring for cardiac surgery in children,44 but using this site for arterial monitoring should generally be avoided because it has poor collateral circulation compared to the radial, femoral, and axillary arteries. Theoretically, there should be a higher incidence of arterial insufficiency with this site, but no studies document this. It should only be used in situations when there are limited other options, e.g. a right upper extremity arterial line is required to monitor pressure during cross-clamping for repair of coarctation of the aorta, or during bypass for aortic arch hypoplasia or interruption.

**Technique**

A 24-gauge catheter should be used in patients under 5 kg. The arm is restrained in neutral position on an armboard, and the arterial impulse is palpated above the elbow crease, well above the bifurcation into the radial and ulnar arteries. Cannulation proceeds as for the radial artery. Meticulous attention to distal perfusion must be paid at all times, and the catheter removed for any signs of ischemia. Pulse oximeter monitoring of distal pulses will provide early detection of perfusion problems. The catheter should be removed or replaced with a catheter in a site with better collateral circulation as soon as possible after the repair.

**Axillary artery**

The axillary artery is large and well collateralized, and several series in critically ill children have demonstrated this to be a viable option with a low complication rate when other sites are not accessible.45,46 However, given the potential morbidity of an ischemic arm and hand, and the theoretical problem of intrathoracic bleeding, this puncture site should be considered a site of last resort when there are limited options.

**Technique**

The arm is abducted 90°, and extended slightly at the shoulder to expose the artery. The artery is palpated high in the axilla, and punctured using an angiocatheter, then exchanged over a guidewire for a longer catheter, or by primary Seldinger technique. A catheter that is too short (e.g. 22-gauge 1″ (25.4 mm) long) will often be pulled out of the vessel with shoulder extension. Therefore, the shortest recommended catheter is 1.97″ (5 cm) long (see Table 7.4). Careful attention must be paid to distal perfusion, as with the brachial artery. Tip position should be ascertained by chest radiograph, and should not lie inside the first rib. The proximity to the
brachiocephalic vessels makes it imperative that the catheter be flushed very gently by hand after blood draws, and that no air bubbles or clots ever be introduced, because of the risk of retrograde cerebral embolization.

Umbilical artery

The umbilical artery is accessible for the first few days of life, and is the site of choice for newborns requiring surgery in the first week of life (see Fig. 7.1). The complication rate is low with low positioning, i.e. tip at the level of third lumbar vertebral body below take off of the renal arteries. The catheter can be left in place for 7–10 days. A relationship to intestinal ischemia and necrotizing colitis has been demonstrated, and enteral feeding with an umbilical artery catheter (UAC) in place is controversial. Umbilical catheters are most commonly inserted by the neonatal staff in the delivery room or neonatal ICU shortly after birth. The technique involves cutting off the umbilical stump with an umbilical tape encircling the base to provide hemostasis, dilating the umbilical artery, and blindly passing a 3.5-Fr catheter a distance based on weight, then assessing position as soon as possible radiographically. Lower extremity emboli, vascular insufficiency, and renal artery thrombosis have all been described; however, the overall risk is low and this site is highly desirable because it is a large central artery yielding accurate pressure monitoring during all phases of the surgery, and preserves access for future interventions.

Temporal artery

The superficial temporal artery at the level just above the zygomatic arch is large and easily accessible in newborns, particularly the premature infant. It was widely used in the 1970s in neonatal nurseries, but rapidly fell out of favor with the realization that significant complications, e.g. retrograde cerebral emboli, were disturbingly common. It should only be used when a brachiocephalic pressure must be measured for the surgery in the face of an aberrant subclavian artery, so that the only way to measure pressure during cross-clamping or on bypass is via direct aortic pressure, or temporal artery pressure. Examples are coarctation of the aorta, aortic arch interruption or hypoplasia, with aberrant right subclavian artery that arises distal to the area of aortic obstruction. The catheter must be used only during the case, blood drawing and flushing should be minimized, and it must be removed as soon as possible after the repair.

Technique

A 24-gauge catheter is used for newborns. The artery is palpated just anterosuperior to the tragus of the ear, just superior to the zygomatic arch. A very superficial angle of approach, i.e. 10–15°, is used, and the artery is cannulated in the same way as described for the radial artery.

Dorsalis pedis/posterior tibial arteries

Superficial foot arteries should not be used for bypass cases, because of the well-known peripheral vasoconstriction and vasomotor instability in the early post-bypass period, which is more pronounced with these arteries than with the radial artery. It is frequently not possible to obtain an accurate arterial pressure waveform in the early post-bypass period. These arteries may be used for non-bypass cases, and in the ICU.

Technique

Dorsalis pedis—the foot is planter flexed slightly to straighten the course of the artery, which is palpated between the second and third metatarsal. A superficial course is taken and the artery cannulated. Posterior tibial—the foot is dorsiflexed to expose the artery between the medial malleolus and the Achilles’ tendon. The artery is often deep to the puncture site, so a steeper angle of incidence is required.

Ulnar artery

The ulnar artery should only be used as a last resort in a desperate situation when other options are not available, because its use is only considered when radial artery attempts have been unsuccessful or thrombosed by past interventions. There is a high risk of ischemia of the hand if both the radial and ulnar artery perfusion is significantly compromised. Despite this, one series of 18 ulnar artery catheters in critically ill infants and children had an ischemia rate not different from radial and femoral artery catheters—5.6%.55

Arterial cutdown

Cutdown of the radial artery is a reliable and often efficient method to establish access for congenital heart surgery. Some centers use this method as the first and primary method of securing arterial access, while others only resort to it when all other attempts fail. Despite the speed and ease of access for a cutdown, available literature indicates a higher rate of bleeding at the site, infection, failure, distal ischemia, and long-term vessel occlusion compared to percutaneous techniques. It is for these reasons that the author’s institution uses cutdowns only when percutaneous methods have failed.

Technique

The arm is positioned as for percutaneous radial catheterization. After surgical preparation and draping, an incision is made at the proximal wrist crease between the styloid process and the flexor carpi radialis tendon, either parallel or perpendicular to the artery. Sharp and blunt dissection is carried out until the artery is identified, and it is isolated with a heavy silk suture, vessel loop or right angle forceps. It is no longer considered necessary to ligate the artery distally to prevent bleeding, and in fact the artery may remain patent...
after a cutdown if not ligated distally. The simplest and very effective technique is to cannulate the exposed artery directly with an angiocatheter, in the same manner as for percutaneous radial artery catheter placement. The catheter is then sutured to the skin at its hub, and the incision closed with nylon sutures on either side of the catheter. Removal entails cutting the suture at the hub of the catheter, removing the catheter, and applying pressure for a few minutes until any bleeding stops. The remaining skin sutures can be removed at a later date.

### Percutaneous pulmonary artery catheterization

Percutaneous PA catheterization has a limited role in congenital heart surgery for several reasons. The small size of many patients precludes placement of adequately sized sheaths and catheters, and most patients have intracardiac shunting, invalidating results of standard thermodilution cardiac output measurements and confusing mixed venous oxygen saturation ($SvO_2$) measurements. In addition, the frequent need for right-sided intracardiac surgery makes PA catheterization undesirable. Thus, when PA pressure or $SvO_2$ monitoring is indicated, transthoracic PA lines are the most common method in congenital heart surgery.

The most common indications for percutaneous PA catheterization in congenital heart surgery are in patients over 6 months of age able to accept a 5- or 6-Fr introducer sheath in the femoral or IJ vein. Patients having surgery on left-heart structures who do not have intracardiac shunting, who are at risk for left ventricular dysfunction, or pulmonary hypertension may benefit from the information available from a PA catheter. Examples include aortic surgery, aortic valve repair or replacement, subaortic resection or myomectomy for hypertrophic cardiomyopathy, mitral valve repair or replacement.

#### Technique

An oximetric catheter is recommended. Commercially available models are 5.5 or 8.5 Fr, and thus require a 6- or 9-Fr sheath, respectively. The 5.5-Fr catheter should be used in patients under 50 kg, and the 8.5 Fr in patients over 50 kg. The sheath is placed into the IJ, femoral, or subclavian veins as described above. The preferred sites of insertion are: (i) right IJ; (ii) left subclavian; or (iii) femoral vein because of the direct path and curvature of the catheter. If an oximetric catheter is used, it is calibrated prior to insertion. The balloon integrity should be tested before insertion by inflating the recommended volume of air or carbon dioxide, and the sterility sleeve is inserted before placement. The PA and CVP ports are connected, flushed, and calibrated before insertion. The PA catheter is inserted 10–15 cm with the balloon deflated, depending on patient size. The balloon is inflated, and the catheter advanced slowly toward the tricuspid valve, whose position is indicated by enlarging V waves on the CVP trace. The catheter is advanced through the tricuspid valve by advancing during diastole until the characteristic right ventricular trace is visible, with no dichrotic notch, and a diastolic pressure of 0–5. Then, the catheter is advanced carefully through the pulmonary valve during systole, until the characteristic PA tracing is visible, with a dichrotic notch and higher diastolic pressure. The catheter is then advanced gently until the pulmonary capillary wedge pressure (PCWP) tracing is obtained, at which time the balloon is deflated so the PA tracing rapidly returns. Difficulty with advancing through the pulmonary valve may be assisted by counterclockwise rotation of the catheter while advancing, positioning the patient right side down and giving a fluid bolus, or by using TEE to visualize the tip and guide subsequent attempts. The catheter must not be left in the wedge position except during brief periods because of the risk of PA rupture and lung ischemia distal to the catheter. During bypass, the catheter can be pulled back several centimeters to reduce the risk of perforation on bypass.

Information obtainable with a PA catheter includes: RA, PA, and PCW pressures. In the absence of mitral valve stenosis or pulmonary venous or arterial hypertension, PA diastolic $\sim$ PCWP $\sim$ left atrial pressure (LAP) $\sim$ left ventricular end-diastolic pressure, which is proportional to left ventricular end-diastolic volume, the classic measure of preload.

Despite the presence of pulmonary hypertension or residual mitral stenosis (diagnosed with postoperative TEE), information from the PA catheter can still be used to direct therapy.

The cardiac index may be measured by standard thermodilution methods, with care taken to input the correct calculation constant into the monitor software according to the catheter size and length, and volume and temperature of injectate. The average of three consecutive injections made in rapid succession at the same point in the respiratory cycle, i.e. expiration, will optimize conditions to achieve an accurate measurement during steady state conditions. Vascular resistances and stroke volume can also be calculated, using the formulae in Table 7.5,61,62

### Hemodynamic data

Hemodynamic data represent only half of the information available from an oximetric PA catheter. The other half consists of oxygen delivery and consumption measurements and calculations, which may also be used to guide therapy in the critically ill patient with low cardiac output syndrome. In the author’s opinion, if the decision has been made to incur the risk and expense of percutaneous PA catheterization, the catheter should be used to its full extent by obtaining all of the information possible to direct therapy, which includes measurement of oxygen delivery and consumption (Table 7.6).61,62 They require either measurement of mixed venous and systemic arterial saturations from blood samples from the tip of the PA catheter and arterial line (measured by cooximetry, not calculated), or substitution of these values with $SvO_2$ from the oximetric catheter (a valid assumption if
increase and maximize both oxygen delivery and consumption may improve outcome, and is a predictor of survival from critical illness, including postoperative cardiac surgery.63–66

Properly calibrated), and the pulse oximeter value instead of measured systemic saturation. There are data from adult and pediatric critical care literature suggesting that the ability to

Table 7.5 Derived hemodynamic parameters.

<table>
<thead>
<tr>
<th>Formula</th>
<th>Normal values</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Adult</td>
</tr>
<tr>
<td>CI = ( \frac{CO}{BSA} )</td>
<td>2.8–4.2 L/min/m²</td>
</tr>
<tr>
<td>SVI = ( \frac{SV}{BSA} )</td>
<td>30–65 mL/beat/m²</td>
</tr>
<tr>
<td>LSVWI = ( \frac{1.36 \cdot (MAP - PCWP) \cdot SVI}{100} )</td>
<td>45–60 g/m²</td>
</tr>
<tr>
<td>RVSWI = ( \frac{1.36 \cdot (PAP - CVP) \cdot SI}{100} )</td>
<td>5–10 g/m²</td>
</tr>
<tr>
<td>SVRI = ( \frac{(MAP - CVP) \cdot 80}{CI} )</td>
<td>1500–2400 dyn · s · cm⁻⁵ · m²</td>
</tr>
<tr>
<td>PVRI = ( \frac{(PAP - PCWP) \cdot 80}{CI} )</td>
<td>250–400 dyn · s · cm⁻⁵ · m²</td>
</tr>
</tbody>
</table>

BSA, body surface area; CI, cardiac index; CO, thermodilution cardiac output; CVP, central venous pressure; LSVWI, left ventricular stroke work index; MAP, mean arterial pressure; PAP, pulmonary artery pressure; PCWP, pulmonary capillary wedge pressure; PVRI, pulmonary vascular resistance index; RVSWI, right ventricular stroke work index; SI, stroke index; SV, stroke volume; SVI, stroke volume index; SVRI, systemic vascular resistance index.

Table 7.6 Derived oxygen delivery/consumption parameters.

<table>
<thead>
<tr>
<th>Formula</th>
<th>Normal values</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Adult</td>
</tr>
<tr>
<td>Arterial ( O_2 ) content</td>
<td>18–20 mL/dL</td>
</tr>
<tr>
<td>( Cao_2 = (1.39 \cdot Hb \cdot Sao_2) + (0.0031 \cdot PaO_2) )</td>
<td></td>
</tr>
<tr>
<td>Mixed venous ( O_2 ) content</td>
<td>13–16 mL/dL</td>
</tr>
<tr>
<td>( Cvo_2 = 1.39 \cdot Hb \cdot Svo_2 + 0.0031 \cdot Pvo_2 )</td>
<td></td>
</tr>
<tr>
<td>Arteriovenous ( O_2 ) content difference</td>
<td>4.0–5.5 mL/dL</td>
</tr>
<tr>
<td>( avDO_2 = Cao_2 - Cvo_2 )</td>
<td></td>
</tr>
<tr>
<td>Pulmonary capillary ( O_2 ) content</td>
<td>19–21 mL/dL</td>
</tr>
<tr>
<td>( Cco_2 = 1.39 \cdot Hb \cdot ScO_2 + 0.0031 \cdot PCO_2 )</td>
<td></td>
</tr>
<tr>
<td>Pulmonary shunt fraction</td>
<td>2–8%</td>
</tr>
<tr>
<td>( Qs/Qt = \frac{100 \cdot (Cco_2 - Cao_2)}{(Cco_2 - Cvo_2)} )</td>
<td></td>
</tr>
<tr>
<td>( O_2 ) delivery index</td>
<td>450–640 mL/min/m²</td>
</tr>
<tr>
<td>( Do_2 = 10 \cdot CO \cdot Cao_2/BSA )</td>
<td></td>
</tr>
<tr>
<td>( O_2 ) consumption index</td>
<td>85–170 mL/min/m²</td>
</tr>
<tr>
<td>( Vo_2 = 10 \cdot CO \cdot (Cao_2 - Cvo_2)/BSA )</td>
<td></td>
</tr>
</tbody>
</table>

BSA, body surface area; \( Cao_2 \), oxygen content of arterial blood; \( Cco_2 \), oxygen content of pulmonary capillary blood; \( Cvo_2 \), oxygen content of mixed venous blood; \( CO \), thermodilution cardiac output; \( Do_2 \), \( O_2 \) delivery index; \( Hb \), hemoglobin; \( Pao_2 \), partial pressure of oxygen in arterial blood; \( PO_2 \), partial pressure of oxygen in pulmonary capillary blood; \( Pvo_2 \), partial pressure of oxygen in mixed venous blood; \( Q_s \), pulmonary shunt blood flow; \( Q_t \), total pulmonary blood flow; \( Sao_2 \), measured arterial oxygen saturation; \( ScO_2 \), measured pulmonary capillary oxygen saturation; \( Svo_2 \), measured mixed venous oxygen saturation.
Ultrasound guidance for vascular access in congenital heart surgery

Numerous studies find ultrasound guidance, either two-dimensional visual ultrasound, or audio Doppler ultrasound, improves the outcome of central venous cannulation, in both children and adults. Use of these methods leads to fewer attempts, decreased insertion time, fewer unintended arterial punctures, and fewer unintended arterial catheter placements. The consensus of many experts in the field of vascular access is that use of these guidance techniques should be considered the standard of care.

A 9.2 MHz pencil thin audio Doppler probe can be gas sterilized and reused (Fig. 7.5). The probe is applied to the site, and the course of the artery and vein are ascertained by their characteristic audio profiles—high pitched, intermittent, systolic flow for the artery, and a low-pitched, continuous venous hum for the vein. The probe is centered over the loudest signal, perpendicular to the skin surface, and the vessel is punctured exactly in the axis of the center of the probe. A “pop” followed by the continuous sound of blood aspiration can often be heard when the vessel is entered. The guidewire, dilator, and catheter are then passed as above. A variation of the audio Doppler technique is a device with the Doppler probe within the needle. However, these needles are expensive, direct comparison has not shown them to be superior to visual ultrasound for cannulation, and because the lumen of the needle is partially occluded with the Doppler probe, flashback of blood is slow and unreliable.

Two-dimensional echocardiography, either in the form of commercially available devices for CVC cannulation only (Site-Rite), or surface probes on standard echocardiography machines, can be used to image large vessels. The color Doppler feature on the latter may be particularly useful to identify desired vessels during difficult vascular access. The desired vessel is localized, e.g. the IJ vein (Fig. 7.6) superficial to and lateral to the carotid artery. The IJ vein is also easily compressible with the probe and is gently pulsatile, while the...
carotid artery is round, difficult to compress with probe pressure, and very pulsatile. The commercially supplied needle guide or midline projection on the screen is used to insert the needle as the probe is held directly over the desired vessel, with the goal of puncturing it exactly in the midline. The needle can be seen indenting and then puncturing the vessel during correct placement. Visual ultrasound is particularly useful to clarify the anatomy after several previous attempts have been made. One can identify the vessel in the midst of a hematoma that has formed, or recognize overlap of the artery and vein. Once the vessel has been punctured and the guidewire passed, the ultrasound can be used to visualize the guidewire in the lumen of the vessel by scanning closer to the heart. Ultrasound methods are most useful for the IJ vein and femoral veins, and less useful for the subclavian. Audio Doppler can be used to assist in the cannulation of any artery, and is particularly useful when pulses are diminished.

**Interpretation of intravascular pressure waveforms**

The normal systemic arterial pressure waveform changes with progression distally from the central arterial circulation, e.g. ascending aorta, distally to the abdominal aorta and femoral arteries, and then to the peripheral arterial such as the radial and foot arteries (Fig. 7.7). In general, the more central sites will produce less peaked systolic pressure waves with slightly lower systolic pressure readings. The dicrotic notch is pronounced in the central arteries. With distal progression, pulse wave amplification will produce a higher peaked systolic pressure wave with a slightly higher systolic pressure. This is most pronounced in the arteries of the foot, where the systolic pressure may be 5–15 torr higher than the ascending aorta. The mean and diastolic pressures change very little with progression. This concept is very important in interpreting arterial pressure tracings. The post-bypass arterial tracing is frequently dampened with catheters in small distal arteries, e.g. radial or foot arteries. This usually resolves within a few minutes after bypass. For particularly long and difficult operations with long bypass and cross-clamp times, it may be useful to place catheters in larger arteries, e.g. femoral or umbilical, or to measure the pressure directly in the aortic root immediately after bypass to ascertain an accurate arterial pressure.

The arterial pressure tracing can yield more information than simply the systolic and diastolic blood pressures. The slope of the upstroke of the pressure wave may be an indicator of systemic ventricular contractility, i.e. the steeper the upstroke, the better the contractility. Significant reductions in contractility flatten the upstroke. The position of the dicrotic notch may give an indication of peripheral vascular resistance. In infants, the normal dicrotic notch is in the upper half of the pressure wave. With low peripheral resistance, as in arterial runoff through a patent ductus arteriosus, the dicrotic notch is lower on the descending limb of the waveform, due to diastolic runoff into the PA, resulting in a relatively longer period of ventricular systole. The area under the curve of the systolic portion of the arterial tracing increases with increased stroke volume. Finally, a hypovolemic patient will often exhibit more pronounced respiratory variation during positive pressure ventilation, as the stroke volume decreases when positive pressure impedes an already limited venous return (Fig. 7.8). Despite common clinical experience demonstrating the utility of the arterial tracing to assess the hemodynamic status of pediatric patients, a recent study compared cardiac index measured by computerized pulse contour analysis of the arterial catheter tracing to transpulmonary thermodilution cardiac index in 16 children after corrective congenital heart surgery. A total of 191 data points were obtained, and a relatively poor correlation of 0.72 with a wide scatter of measurements was found, suggesting that this method is not reliable in estimating cardiac output.

Recently developed technology uses an arterial catheter and a CVC, along with an injection of contrast, to measure cardiac output by either thermodilution or lithium dilution. Both methods have demonstrated good correlation with standard thermodilution via a PA catheter, but are less invasive. Technical limitations exist for pediatric patients but these
Under no circumstances should a bubble be intentionally introduced into the system to produce an increased damping effect. Appropriateness of resonance frequency may be tested by flushing the system from a pressurized bag of heparinized saline, stopping suddenly, and observing the number and amplitude of oscillations required to return to baseline waveform. Proper damping is signified by one oscillation below, and one above, the mean before return to normal waveform,76,77

Failure of arterial pressure monitoring systems is always possible during congenital heart surgery. Causes of monitoring failure include kinking or clotting of the catheter, or spasm of the artery. Additional causes may include compression of an aberrant right subclavian artery from a TEE probe, or compression of an axillary artery from a sternal retractor. A back-up oscillometric blood pressure cuff should always be present. In addition, a reasonable precaution is to have the groins prepped into the field so the surgeon can place a catheter in the femoral artery percutaneously or by cutdown.

Central venous, right and left atrial waveforms

Normal atrial (i.e. central venous) pressure waveforms consist of the A, C, and V waves corresponding to atrial contraction, closure of the tricuspid or mitral valves, and ventricular contraction. Normal right atrial A-wave pressure is lower than V-wave pressure, which is usually less than 10 mmHg. Changes from the normal tracing can give important information about the hemodynamic status and cardiac rhythm of the patient. For example, when atrioventricular synchrony is lost, as in junctional ectopic tachycardia or supraventricular tachycardia, the A wave disappears, and the V wave enlarges considerably, reflecting backwards transmission of ventricular pressure through an ineffectively emptied atrium (Fig. 7.9). Determining the cardiac rhythm from the ECG is often difficult at rapid heart rates because the P wave of the ECG is indiscernible. The left or right atrial waveform can give crucial added information in this situation, clearly retaining the A wave in cases of sinus tachycardia. Competency of the atrioventricular (AV) valves can also be assessed from the atrial tracing. Mitral or tricuspid regurgitation will produce a large V wave on the atrial tracing. It is often very useful to record the vascular pressure tracings in sinus rhythm at baseline for later comparison.

Vascular access in newborns requiring cardiac surgery

Many patients requiring surgery in the first 2 weeks of life will need future surgery or cardiac catheterization. The goals for vascular access in this group of patients include preserving patency of the IVC and SVC and the distal vessels draining into them, i.e. femoral-iliac veins and innominate-jugular
veins. This is particularly important for single ventricle patients who all will require future catheter and surgical interventions. The risk of vessel occlusion in newborn patients with standard catheters of 3 Fr size or larger is at least 5.8% for a catheter left in 7 days or longer, and thrombosed vessels preclude their use in the future. Thrombosis of the SVC is a life-threatening complication, because future cavopulmonary anastomosis becomes extremely difficult or impossible. Therefore, the SVC catheterization should be avoided in the newborn period unless there is no other alternative.

**Complications of vascular access**

**Thrombosis**

This is the single most frequent complication, especially among infants. Central venous thrombosis develops in 5.8% of neonatal patients, which is ten times that of older patients, and accounts for 40–50% of central venous thromboses after congenital heart surgery. The frequency significantly decreases in patients over 6 months of age. Factors that contribute to the risk of thrombosis include: (i) large bore catheters in small vessels, i.e. larger than 4 Fr in small infants; (ii) duration of cannulation exceeding 7 days; (iii) venous stasis due to extreme fluid restriction or low cardiac output; (iv) infusion of high osmolarity fluids, i.e. concentrated dextrose in parenteral nutrition fluids; and (v) hypercoagulable states. Immediate consequences of SVC thrombosis include SVC syndrome with increased intracranial pressure, and chylothorax from ineffective drainage of the thoracic duct into the SVC. Inferior vena cava thrombus leads to ascites, renal and intestinal dysfunction, and edema of the lower abdomen and extremities. The patient must be assessed carefully for signs of thrombosis, and suspicion of thrombosis should be evaluated by ultrasound examination. Treatment modalities include removing the catheter, heparinization, thrombolytic agents such as tissue plasminogen activator and urokinase, antithrombin III replacement, and surgical thrombectomy. Mortality from SVC thrombosis is reported to be as high as 33% and therefore it is critical to try to prevent this complication, preferably by avoiding SVC catheters in patients under 4 kg. Thrombosis also leads to a higher rate of infection. Heparin-bonded catheters decrease the rate of thrombosis and do not increase the risk of bleeding; however, it is currently not possible to bond both heparin and antibiotics to the same catheter. In patients with occlusion of central veins from previous catheters, magnetic resonance venography may be useful in identifying patent veins for future interventions.

Thrombosis or dissection of an artery is a serious complication that must be treated immediately. Immediately after arterial catheter placement it is important to inspect the distal extremity, comparing it to the other extremity, and palpate distal pulses. Placement of a pulse oximeter probe distal to the catheter serves as a continuous monitor and early warning of vascular insufficiency. Transient compromise to perfusion immediately after catheter placement due to arterial spasm or during low output states may be observed. However, when extremity perfusion is significantly compromised, treatment by removal of the catheter, surgical consultation, use of vasodilators, warming the extremity, heparin, thrombolytics, surgical thrombectomy, or surgical reconstruction is indicated.

**Malposition/perforation**

Central venous catheter tips should not lie in the RA. Adult and pediatric studies have consistently demonstrated a higher rate of heart and great vessel perforation with associated cardiac tamponade when catheter tips are in the atrium. Perforation is also less common with right-sided lines, e.g. right IJ or subclavian, because the catheter tip is parallel to the vein wall. The catheter tip of left-sided lines are frequently at a 45–90° angle of incidence to the SVC or atrium, and mechanical models demonstrate that this position is more likely to lead to great vessel perforation. Finally, 5–10% of patients with congenital heart disease have a left SVC, which most often drains into the coronary sinus or left atrium, and both of these sites are undesirable locations for a catheter tip. Thus the ideal position of a CVC is in the mid-SVC with the tip parallel to the vein wall.
Umbilical venous catheters should be above the level of the pericardial reflection. Many authorities recommend positioning the tip of the catheter in the superior half of the SVC, above the pericardial reflection. This recommendation is based on the theoretical concept that if there is a perforation, cardiac tamponade will not be produced, and also the catheter tip will be above the SVC bypass cannula and thus yield accurate CVP measurements on bypass. There are several problems with this approach in congenital heart surgery, particularly in small patients. First the SVC is often only 4–5 cm long, leaving little room for error in placement. It is preferable to have the catheter slightly too deep in the SVC, because this will lead to accurate pressure measurements and proper infusions of drugs and fluids. When a multilumen catheter is positioned too cephalad in the SVC, one of the proximal ports may not be inside the jugular vein, leading to extravascular extravasation of important or caustic drugs and fluids. In addition, the pericardium is usually opened in congenital heart surgery and drained postoperatively, rendering placement above the pericardial reflection moot. Many series of catheter placements in children document that the IJ route results in very posterior and the tip is posterior to the vertebral bodies. The catheter must be removed immediately and the patient assessed for neurologic deficit if this malposition is discovered.

Inadvertent arterial puncture can nearly always be prevented by the use of an ultrasound guidance system for CVC placement (see above). However, if this complication occurs, the following general principles are useful. After needle puncture if there is any question about whether the vessel is an artery, remove the needle immediately, elevate the area, and hold firm pressure for 5–10 min. A small bore needle puncture of the carotid or femoral artery, e.g. 20 gauge or smaller, is not usually an indication to cancel surgery. If a larger hole is created in the artery, i.e. a dilator and the catheter have been placed, pressure transduction can be used to confirm location. In this case, a discussion with the surgeon must ensue. Normally, the catheter can be removed, and pressure held without consequences unless a very large catheter was used, e.g. introducer sheath or large-bore CVP catheter, in which case surgical exploration and repair should be undertaken. In most cases of elective cardiac surgery, it is prudent to postpone the case if a large hole has been made in the artery. The case can usually be safely performed 24 hours later if no bleeding has occurred. In emergency or urgent cases that must proceed despite a large hole in the artery, the neck or groin should be prepped into the field for exploration if excessive bleeding or hematoma formation occur.

**Pneumothorax**

This complication is most frequent with the subclavian approach, but also may occur with the IJ approach, especially with the low puncture sites, e.g. jugular notch approach. To avoid this complication with the subclavian approach it is important to advance the needle only during expiration. A very shallow approach with the needle directed just posterior to the clavicle and at the sternal notch is also important. For the IJ vein, a higher puncture site and limiting the caudad advancement of the needle to stop above the clavicle will usually prevent this complication.

Continuous aspiration should be performed as the needle is advanced using a saline-filled syringe. If air is aspirated as the needle is advanced, attempts at venipuncture should stop immediately, and careful monitoring for compromise of ventilation and hemodynamics should ensue. A chest radiograph should be obtained to make the diagnosis, and pleural drainage by needle, catheter, or tube should be undertaken if indicated. After sternotomy the pleura can be opened on that side during sternotomy if pneumothorax is diagnosed or suspected.

**Infection**

Catheter-related sepsis results in significant morbidity, some mortality, prolongation of ICU stay, and increased expense.
The incidence of arterial catheter-related infection is low. A study of 340 arterial catheters in children revealed a 2.3% incidence of local site infection, and 0.6% catheter sepsis. There is strong evidence that several strategies may be employed to reduce this complication. The first is the use of full barrier precautions, e.g. sterile gown, mask, gloves, and careful septic technique during insertion. Second, chlorhexidine has been shown to be superior to other antiseptic solutions. Finally antibiotic bonding to the resin of the catheter will reduce infection. This can be done in several ways, e.g. antibiotics already embedded in the resin (minocycline/ rifampin or chlorhexidine/silver sulfadiazine), or applied at the time of insertion by soaking the outer and inner surfaces of a special catheter in a negatively charged antibiotic at 100 mg/mL concentration (such as vancomycin, cefazolin, or other cephalosporins). Antibiotic is slowly released from the catheter, delaying and reducing colonization, and reducing the incidence of catheter sepsis. The increased cost per catheter is about $20, but one episode of catheter sepsis is estimated to cost $14,000 in 1995 dollars. Central venous catheters indwelling more than 5–7 days have an increased incidence of colonization and sepsis, as well as vessel thrombosis. Suspicion of catheter sepsis should be followed by peripheral blood culture, and blood culture from the central line. The catheter should be removed when possible and the tip cultured. Antibiotic therapy is empirically tailored to the most common institution-specific pathogens, and should provide coverage for Staphylococcus epidermidis, which continues to be a common pathogen in catheter-related sepsis.

Arrhythmias

Other complications associated with vascular access procedures include arrhythmias. Ectopic atrial tachycardia, in particular, has been associated with a catheter tip in the RA. Atrial fibrillation has also been associated with CVC placement. More commonly, arrhythmias occur with the passage of the guidewire, and include isolated PACs, supraventricular tachycardia, and if the guidewire is advanced into the right ventricle, premature ventricular contractions and even ventricular tachycardia or fibrillation. Great care must be taken when passing the guidewire to stop advancing it when significant arrhythmias are encountered, and when advancing the catheter over the wire to retract the wire as the catheter is advanced. Patients particularly at risk for significant arrhythmia are those with a known history of arrhythmia, and also those with significant right ventricular hypertrophy.

Systemic air embolus

Systemic air embolus is a constant threat for patients with central or peripheral venous catheters and intracardiac shunting, particularly two ventricle patients with right-to-left shunting, and single ventricle patients in infancy who have obligate mixing of systemic and pulmonary venous return in the systemic ventricle. Air may lodge in the coronary arteries, especially the right, PA, or brain, leading to potentially serious complications. Observation of the transesophageal echocardiogram, or transcranial Doppler ultrasound as used for neurologic monitoring, reveals rapid passage of any introduced systemic venous air into the aorta and cerebral circulation. For this reason, meticulous attention must be paid to prevent the introduction of air into the systemic venous circulation as much as possible. Precautions include thorough de-airing of all intravenous infusions before connection to the patient, de-airing of continuous flush central venous lines, air filters on continuous infusions, and careful technique when injecting drugs and fluids. The latter involves holding any syringe upright, flushing fluid from the proximal intravenous tubing into it, and aspirating and tapping the syringe first before injecting so that any air is trapped at the superior aspect of the syringe. Constant vigilance of all infusions and the use of TEE as a monitor for intracardiac air and the transcranial Doppler for systemic arterial air may reduce the risk of significant air embolus.

Other complications

Thoracic duct injury, chylothorax, brachial plexus injury, cervical dural puncture, phrenic nerve injury, vertebral arteriovenous fistula, Horner’s syndrome, and tracheal puncture have also been described. These complications can essentially be eliminated with skilled personnel using ultrasound guided techniques to accurately identify the location of the vessel.

Finally, embolization of catheter or guidewire fragments sheared off during difficult insertion procedures occasionally occur. Never withdraw a guidewire or catheter through a needle if any resistance is encountered. If resistance is encountered, the guidewire and needle, or catheter and needle, must be withdrawn completely from the vessel together as a unit.

Conclusion

Vascular access is a critical issue for every patient undergoing congenital heart surgery. Each team of practitioners develops its own approach to vascular access, and no one approach, e.g. transthoracic vs. percutaneous CVCs, or percutaneous vs. cutdown radial artery access, has been demonstrated to be superior to any other. Complication rates, time for insertion, and expense are significant. Application of the principles of safe insertion, particularly a strategy to preserve access sites in small single-ventricle patients, ultrasound guidance of catheter placement, and the use of antibiotic-impregnated catheters, will improve the outcome of vascular access procedures.
References


PART 2 Monitoring


