One of the most dramatic events in medical self-experimentation took place in a small German hospital during the summer of 1929 when a 25 year old surgical resident named Werner Forssman inserted a plastic urethral catheter into the basilic vein in his right arm and then advanced the catheter into the right atrium of his heart (1). This was the first documented instance of central venous cannulation using a flexible plastic catheter. Although a success, the procedure had only one adverse consequence; i.e., Dr. Forssman was immediately dismissed from his residency because he had acted without the consent of his superiors, and his actions were perceived as reckless and even suicidal. Upon dismissal, he was told that “such methods are good for a circus but not for a respected hospital” (1). Forssman went on to become a country doctor, but his achievement in vascular cannulation was finally recognized in 1956 when he was awarded the Nobel Prize in Medicine for performing the first right-heart catheterization in a human subject.

Werner Forssman’s self-catheterization was a departure from the standard use of needles and rigid metal cannulas for vascular access, and it marked the beginning of the modern era of vascular cannulation, which is characterized by the use of flexible plastic catheters like the ones described in this chapter.

CATHETER BASICS

Catheter Material

Vascular catheters are made of synthetic polymers that are chemically inert, biocompatible, and resistant to chemical and thermal degradation. The most widely used polymers are polyurethane and silicone.
Polyurethane

Polyurethane is a versatile polymer that can act as a solid (e.g., the solid tires on lawn mowers are made of polyurethane) and can be modified to exhibit elasticity (e.g., Spandex fibers used in stretchable clothing are made of modified polyurethane). The polyurethane in vascular catheters provides enough tensile strength to allow catheters to pass through the skin and subcutaneous tissues without kinking. Because this rigidity can also promote vascular injury, polyurethane catheters are used for short-term vascular cannulation. Most of the vascular catheters you will use in the ICU are made of polyurethane, including peripheral vascular catheters (arterial and venous), central venous catheters, and pulmonary artery catheters.

Silicone

Silicone is a polymer that contains the chemical element silicon together with hydrogen, oxygen, and carbon. Silicone is more pliable than polyurethane (e.g., the nipple on baby bottles is made of silicone), and this reduces the risk of catheter-induced vascular injury. Silicone catheters are used for long-term vascular access (weeks to months), such as that required for prolonged administration of chemotherapy, antibiotics, and parenteral nutrition solutions in outpatients. The only silicone-based catheters inserted in the ICU setting are peripherally-inserted central venous catheters (PICCs). Because of their pliability, silicone catheters cannot be inserted percutaneously without the aid of a guidewire or introducer sheath.

Catheter Size

The size of vascular catheters is determined by the outside diameter of the catheter. There are two measures of catheter size: the gauge size and the “French” size.

Gauge Size

The gauge system was introduced (in England) as a sizing system for iron wires, and was later adopted for hollow needles and catheters. Gauge size varies inversely with outside diameter (i.e., the higher the gauge size, the smaller the outside diameter); however, there is no fixed relationship between gauge size and outside diameter. The International Organization for Standardization (ISO) has proposed the relationships shown in Table 1.1 for gauge sizes and corresponding outside diameters in peripheral catheters (2). Note that each gauge size is associated with a range of outside diameters (actual OD), and further that there is no fixed relationship between the actual (measured) and nominal outside diameters. Thus, the only way to determine the actual outside diameter of a catheter is to consult the manufacturer. Gauge sizes are typically used for peripheral catheters, and for the infusion channels of multilumen catheters.

French Size

The French system of sizing vascular catheters (named after the country
of origin) is superior to the gauge system because of its simplicity and uniformity. The French scale begins at zero, and each increment of one French unit represents an increase of 1/3 (0.33) millimeter in outer diameter (3): i.e., French size \( \times 0.33 = \) outside diameter (mm). Thus, a catheter that is 5 French units in size will have an outer diameter of 5 \( \times 0.33 = 1.65 \) mm. (A table of French sizes and corresponding outside diameters is included in Appendix 2 in the rear of the book.) French sizes can increase indefinitely, but most vascular catheters are between 4 French and 10 French in size. French sizes are typically used for multilumen catheters and for large-bore single lumen catheters (like introducer sheaths, described later in the chapter).

**Table 1.1** Gauge Sizes & Outside Diameters for Peripheral Catheters†

<table>
<thead>
<tr>
<th>Gauge</th>
<th>Range of Actual OD (mm)</th>
<th>Nominal OD (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>24</td>
<td>0.65 – 0.749</td>
<td>0.7</td>
</tr>
<tr>
<td>22</td>
<td>0.75 – 0.949</td>
<td>0.8, 0.9</td>
</tr>
<tr>
<td>20</td>
<td>0.95 – 1.149</td>
<td>1.0, 1.1</td>
</tr>
<tr>
<td>18</td>
<td>1.15 – 1.349</td>
<td>1.2, 1.3</td>
</tr>
<tr>
<td>16</td>
<td>1.55 – 1.849</td>
<td>1.6, 1.7, 1.8</td>
</tr>
<tr>
<td>14</td>
<td>1.85 – 2.249</td>
<td>1.9, 2.0, 2.1, 2.2</td>
</tr>
</tbody>
</table>

†From the International Organization for Standardization; ISO 10555-5; 1996 (available at www.iso.org). OD = outside diameter.

**Catheter Flow**

Steady flow \((Q)\) through a hollow, rigid tube is proportional to the pressure gradient along the length of the tube \((P_{in} - P_{out}, \text{ or } \Delta P)\), and the constant of proportionality is the resistance to flow \((R)\):

\[
Q = \Delta P \times 1/R
\]  

(1.1)

The properties of flow through rigid tubes was first described by a German physiologist (Gotthif Hagen) and a French physician (Jean Louis Marie Poiseuille) working independently in the mid-19th century. They both observed that flow \((Q)\) through rigid tubes is a function of the inner radius of the tube \((r)\), the length of the tube \((L)\) and the viscosity of the fluid \((\mu)\). Their observations are expressed in the equation shown below, which is known as the *Hagen-Poiseuille equation* (4).

\[
Q = \Delta P \times (\pi r^4 / 8\mu L)
\]  

(1.2)

This equation states that the steady flow rate \((Q)\) in a rigid tube is directly related to the fourth power of the inner radius of the tube \((r^4)\), and is inversely related to the length of the tube \((L)\) and the viscosity of the fluid \((\mu)\). The term enclosed in parentheses \((\pi r^4 / 8\mu L)\) is equivalent to the reciprocal of resistance \((1/R, \text{ as in equation 1.1})\), so the resistance to flow can be expressed as \(R = 8\mu L / \pi r^4\).
Since the Hagen-Poiseuille equation applies to flow through rigid tubes, it can be used to describe flow through vascular catheters, and how the dimensions of a catheter can influence the flow rate (see next).

**Inner Radius and Flow**

According to the Hagen-Poiseuille equation, the inner radius of a catheter has a profound influence on flow through the catheter (because flow is directly related to the fourth power of the inner radius). This is illustrated in Figure 1.1, which shows the gravity-driven flow of blood through catheters of similar length but varying outer diameters (5). (In studies such as this, changes in inner and outer diameter are considered to be equivalent.) Note that the relative change in flow rate is three times greater than the relative change in catheter diameter ($\Delta \text{flow}/\Delta \text{diameter} = 3$). Although the magnitude of change in flow in this case is less than predicted by the Hagen-Poiseuille equation (a common observation, with possible explanations that are beyond the scope of this text), the slope of the graph in Figure 1.1 clearly shows that changes in catheter diameter have a marked influence on flow rate.

**Catheter Length and Flow**

The Hagen-Poiseuille equation indicates that flow through a catheter will decrease as the length of the catheter increases, and this is shown in
Figure 1.2. (6) Note that flow in the longest (30 cm) catheter is less than half the flow rate in the shortest (5 cm) catheter; in this case, a 600% increase in catheter length is associated with a 60% reduction in catheter flow ($\Delta\text{flow}/\Delta\text{length} = 0.1$). Thus, the influence of catheter length on flow rate is proportionately less than the influence of catheter diameter on flow rate, as predicted by the Hagen-Poiseuille equation.

The comparative influence of catheter diameter and catheter length, as indicated by the Hagen-Poiseuille equation and the data in Figures 1.1 and 1.2, indicates that when rapid volume infusion is necessary, a large-bore catheter is the desired choice, and the shortest available large-bore catheter is the optimal choice. (See Chapter 11 for more on this subject.) The flow rates associated with a variety of vascular catheters are presented in the remaining sections of this chapter.

**COMMON CATHETER DESIGNS**

There are three basic types of vascular catheters: peripheral vascular catheters (arterial and venous), central venous catheters, and peripherally inserted central catheters.
Peripheral Vascular Catheters

The catheters used to cannulate peripheral blood vessels in adults are typically 16–20 gauge catheters that are 1–2 inches in length. Peripheral catheters are inserted using a catheter-over-needle device like the one shown in Figure 1.3. The catheter fits snugly over the needle and has a tapered end to prevent fraying of the catheter tip during insertion. The needle has a clear hub to visualize the “flashback” of blood that occurs when the tip of the needle enters the lumen of a blood vessel. Once flashback is evident, the catheter is advanced over the needle and into the lumen of the blood vessel.

![Figure 1.3](image1.png)

**FIGURE 1.3** A catheter-over-needle device for the cannulation of peripheral blood vessels.

The characteristics of flow through peripheral catheters are demonstrated in Table 1.2 (7,8). Note the marked (almost 4-fold) increase in flow in the larger-bore 16 gauge catheter when compared to the 20 gauge catheter and also note the significant (43%) decrease in flow rate that occurs when the length of the 18 gauge catheter is increased by less than one inch. These observations are consistent with the relationships in the Hagen-Poiseuille equation, and they demonstrate the power of catheter diameter in determining the flow capacity of vascular catheters.

<table>
<thead>
<tr>
<th>Gauge Size</th>
<th>Length</th>
<th>Flow Rate</th>
<th>mL/min</th>
<th>L/hr</th>
</tr>
</thead>
<tbody>
<tr>
<td>16</td>
<td>30 mm</td>
<td>220</td>
<td></td>
<td>13.2</td>
</tr>
<tr>
<td>18</td>
<td>30 mm</td>
<td>105</td>
<td></td>
<td>6.0</td>
</tr>
<tr>
<td></td>
<td>50 mm</td>
<td>60</td>
<td></td>
<td>3.6</td>
</tr>
<tr>
<td>20</td>
<td>30 mm</td>
<td>60</td>
<td></td>
<td>3.6</td>
</tr>
</tbody>
</table>

From References 6 and 7. All flow rates are for gravity-driven flow of water.
Central Venous Catheters

Cannulation of larger, more centrally placed veins (i.e., subclavian, internal jugular, and femoral veins) is often necessary for reliable vascular access in critically ill patients. The catheters used for this purpose, commonly known as central venous catheters, are typically 15 to 30 cm (6 to 12 inches) in length, and have single or multiple (2–4) infusion channels. Multilumen catheters are favored in the ICU because the typical ICU patient requires a multitude of parenteral therapies (e.g., fluids, drugs, and nutrient mixtures), and multilumen catheters make it possible to deliver these therapies using a single venipuncture. The use of multiple infusion channels does not increase the incidence of catheter-related infections (9), but the larger diameter of multilumen catheters creates an increased risk of catheter-induced thrombosis (10).

Triple-lumen catheters like the one shown in Figure 1.4 are the consensus favorite for central venous access. These catheters are available in diameters of 4 French to 9 French, and the 7 French size (outside diameter = 2.3 mm) is a popular choice in adults. Size 7 French triple lumen catheters typically have one 16 gauge channel and two smaller 18 gauge channels. To prevent mixing of infusate solutions, the three outflow ports are separated as depicted in Figure 1.4.

The features of triple lumen catheters (7 French size) from one manufacturer are shown in Table 1.3. Note the much slower flow rates in the 16 gauge and 18 gauge channels when compared to the 16 and 18 gauge peripheral catheters in Table 1.2. This, of course, is due to the much longer length of central venous catheters, as predicted by the Hagen-Poiseuille
equation. There are 3 available lengths for the triple lumen catheter: the shortest (16 cm) catheters are intended for right-sided catheter insertions, while the longer (20 cm and 30 cm) catheters are used in left-sided cannulations (because of the longer path to the superior vena cava). The 20 cm catheter is long enough for most left-sided cannulations so (to limit catheter length and thereby preserve flow), it seems wise to avoid central venous catheters that are longer than 20 cm, if possible.

### Table 1.3 Selected Features of Triple-Lumen Central Venous Catheters

<table>
<thead>
<tr>
<th>Size</th>
<th>Length</th>
<th>Lumens</th>
<th>Lumen Size</th>
<th>Flow Rate (L/hr)†</th>
</tr>
</thead>
<tbody>
<tr>
<td>7 Fr</td>
<td>16 cm</td>
<td>Distal</td>
<td>16 ga</td>
<td>3.4</td>
</tr>
<tr>
<td></td>
<td>(6 in)</td>
<td>Medial</td>
<td>18 ga</td>
<td>1.8</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Proximal</td>
<td>18 ga</td>
<td>1.9</td>
</tr>
<tr>
<td>7 Fr</td>
<td>20 cm</td>
<td>Distal</td>
<td>16 ga</td>
<td>3.1</td>
</tr>
<tr>
<td></td>
<td>(8 in)</td>
<td>Medial</td>
<td>18 ga</td>
<td>1.5</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Proximal</td>
<td>18 ga</td>
<td>1.6</td>
</tr>
<tr>
<td>7 Fr</td>
<td>30 cm</td>
<td>Distal</td>
<td>16 ga</td>
<td>2.3</td>
</tr>
<tr>
<td></td>
<td>(12 in)</td>
<td>Medial</td>
<td>18 ga</td>
<td>1.0</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Proximal</td>
<td>18 ga</td>
<td>1.1</td>
</tr>
</tbody>
</table>

†All flow rates are for gravity-driven flow of isotonic saline from a height of 40 inches above the catheters. Fr = French size; ga = gauge size.
From Arrow International (www.arrowintl.com); accessed 8/1/2011.

### Insertion Technique

Central venous catheters are inserted by threading the catheter over a guidewire (a technique introduced in the early 1950s and called the Seldinger technique after its founder). This technique is illustrated in Figure 1.5. A small bore needle (usually 20 gauge) is used to probe for the target vessel. When the tip of the needle enters the vessel, a long, thin wire with a flexible tip is passed through the needle and into the vessel lumen. The needle is then removed, and a catheter is advanced over the guidewire and into the blood vessel. When cannulating deep vessels, a larger and more rigid “dilator catheter” is first threaded over the guidewire to create a tract that facilitates insertion of the vascular catheter.

### Antimicrobial Catheters

Central venous catheters are available with two types of antimicrobial coating: one uses a combination of chlorhexidine and silver sulfadiazine (available from Arrow International, Reading PA), and the other uses a combination of minocycline and rifampin (available from Cook Critical Care, Bloomington, IN). Each of these antimicrobial catheters has proven effective in reducing the incidence of catheter-related septicemia (11,12).
A single multicenter study comparing both types of antimicrobial coating showed superior results with the minocycline-rifampin catheters (13). A

FIGURE 1.5 The steps involved in guidewire-assisted cannulation of blood vessels (the Seldinger technique).
design flaw in the chlorhexidine-silver sulfadiazine catheter (i.e., no antimicrobial activity on the luminal surface of the catheter) has since been corrected, but a repeat comparison study has not been performed. Therefore, the evidence at the present time favors the minocycline rifampin catheters as the most effective antimicrobial catheters in clinical use (12). This situation could (and probably will) change in the future.

What are the indications for antimicrobial catheters? According to the most recent guidelines on preventing catheter-related infections (14), antimicrobial catheters should be used if the expected duration of central venous catheterization is > 5 days and if the rate of catheter-related infections in your ICU is unacceptably high despite other infection control efforts.

<table>
<thead>
<tr>
<th>Table 1.4</th>
<th>Selected Features of Peripherally Inserted Central Catheters</th>
</tr>
</thead>
<tbody>
<tr>
<td>Size</td>
<td>Length</td>
</tr>
<tr>
<td>5 Fr</td>
<td>50 cm (195 in)</td>
</tr>
<tr>
<td>5 Fr</td>
<td>70 cm (27.5 in)</td>
</tr>
<tr>
<td>5 Fr</td>
<td>50 cm (19.5 in)</td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td>5 Fr</td>
<td>70 cm (27.5 in)</td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
</tbody>
</table>

†All flow rates are for gravity-driven flow of isotonic saline from a height of 40 inches above the catheters. Fr = French size; ga = gauge size.
From Arrow International (www.arrowintl.com); accessed 8/1/2011.

**Peripherally Inserted Central Catheters**

Concern for the adverse consequences of central venous cannulation (e.g., pneumothorax arterial puncture, poor patient acceptance) prompted the introduction of *peripherally inserted central catheters* (PICCs), which are inserted in the basilic or cephalic vein in the arm (just above the antecubital fossa) and advanced into the superior vena cava (15). (Insertion of PICCs is described in the next chapter). In the ICU, PICCs are used primarily when traditional central venous access sites are considered risky (e.g., severe thrombocytopenia) or are difficult to obtain (e.g., morbid obesity).

The characteristics of PICC devices from one manufacturer are shown in Table 1.4. These catheters are smaller in diameter than central venous catheters because they are introduced into smaller veins. However, the major distinction between PICCs and central venous catheters is their
length; i.e., the length of the catheters in Table 1.4 (50 cm and 70 cm) is at least double the length of the triple lumen catheters in Table 1.3. The tradeoff for this added length is a reduction in flow capacity, which is evident when comparing the flow rates in Table 1.4 and Table 1.3. Flow is particularly sluggish in the double lumen PICCs because of the smaller diameter of the infusion channels. The flow limitation of PICCs (especially the double lumen catheters) makes them ill-suited for aggressive volume therapy.

SPECIALTY CATHETERS

The catheters described in this section are designed to perform specific tasks, and are otherwise not used for patient care. These specialty devices include hemodialysis catheters, introducer sheaths, and pulmonary artery catheters.

Hemodialysis Catheters

One of the recognized benefits of intensive care units is the ability to provide emergent hemodialysis for patients with acute renal failure, and this is made possible by a specially designed catheter like the one shown in Figure 1.6. The features of this catheter are shown in Table 1.5.

Hemodialysis catheters are the wide-body catheters of critical care, with diameters up to 16 French (5.3 mm), and they are equipped with dual 12 gauge infusion channels that can accommodate the high flow rates (200–300 mL/min) needed for effective hemodialysis. One channel carries blood from the patient to the dialysis membranes, and the other channel returns the blood to the patient.

Hemodialysis catheters are usually placed in the internal jugular vein and are left in place until alternate access is available for dialysis. Cannulation of the subclavian vein is forbidden because of the propensity for subclavian vein stenosis (16), which hinders venous outflow from the ipsilateral arm and thereby prevents the use of that arm for chronic hemodialysis access with an arteriovenous shunt.

### Table 1.5 | Selected Features of Hemodialysis Catheters

<table>
<thead>
<tr>
<th>Size</th>
<th>Length</th>
<th>Lumens</th>
<th>Lumen Size</th>
<th>Flow Rate (L/hr)†</th>
</tr>
</thead>
<tbody>
<tr>
<td>12 Fr</td>
<td>16 cm (6 in)</td>
<td>Proximal</td>
<td>12 ga</td>
<td>23.7</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Distal</td>
<td>12 ga</td>
<td>17.4</td>
</tr>
<tr>
<td>12 Fr</td>
<td>20 cm (8 in)</td>
<td>Proximal</td>
<td>16 ga</td>
<td>19.8</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Distal</td>
<td>12 ga</td>
<td>15.5</td>
</tr>
</tbody>
</table>

†All flow rates are for gravity-driven flow of isotonic saline from a height of 40 inches above the catheters. Fr = French size; ga = gauge size.

From Arrow International (www.arrowintl.com); accessed 8/1/2011.
Introducer Sheaths

Introducer sheaths are large-bore (8–9 French) catheters that serve as conduits for the insertion and removal of temporary vascular devices. In the ICU, they are used primarily to facilitate the placement of pulmonary artery (PA) catheters (see Figure 8.1 for an illustration of an introducer sheath and its companion PA catheter). The introducer sheath is first placed in a large, central vein, and the PA catheter is then threaded through the sheath and advanced into the pulmonary artery. The placement of PA catheters often requires repeated trials of advancing and retracting the catheter to achieve the proper position in the pulmonary artery, and the introducer sheath facilitates these movements. When the PA catheter is no longer needed, the introducer sheath allows the catheter to be removed and replaced with a central venous catheter, if needed, without a new venipuncture.

Rapid Infusion

Introducer sheaths can also serve as stand-alone infusion devices by virtue of a side infusion port on the hub of the catheter. The large diameter of introducer sheaths has made them popular as rapid infusion devices for the management of acute blood loss. When introducer sheaths are used with pressurized infusion systems, flow rates of 850 mL/min have been reported (17). The use of introducer sheaths for rapid volume infusion is revisited in Chapter 11.
Pulmonary Artery Catheters

Pulmonary artery balloon-flotation catheters are highly specialized devices capable of providing as many as 16 measures of cardiovascular function and systemic oxygenation. These catheters have their own chapter (Chapter 8), so proceed there for more information.

A FINAL WORD

The performance of vascular catheters as infusion devices is rooted in the Hagen–Poiseuille equation, which describes the influence of catheter dimensions on flow rate. The following statements from this equation are part of the “essential knowledge base” for vascular catheters.

1. Flow rate is directly related to the inner radius of a catheter (i.e., both vary in the same direction), and is inversely related to the length of the catheter (i.e., vary in opposite directions).
2. The inner radius (lumen size) of a catheter has a much greater influence on flow rate than the length of the catheter.
3. For rapid infusion, a large bore catheter is essential, and a short, large bore catheter is optimal.

As for the performance of individual catheters, each ICU has its own stock of vascular catheters, and you should become familiar with the sizes and flow capabilities of the catheters that are available.

REFERENCES


**Common Catheter Designs**


**Specialty Catheters**
