Shunt Detection and Quantification

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Detection, localization, and quantification of intracardiac shunts are an integral part of the hemodynamic evaluation of patients with congenital heart disease. In most cases, an intracardiac shunt is suspected on the basis of the clinical evaluation of the patient before catheterization. There are several circumstances, however, in which data obtained at catheterization should alert the cardiologist to look for a shunt that had not been suspected previously:

1. Unexplained arterial desaturation should immediately raise the suspicion of a right-to-left intracardiac shunt, which may then be assessed by the methods to be discussed. Most commonly, arterial desaturation (i.e., arterial blood oxygen saturation <95%) detected at the time of cardiac catheterization represents alveolar hypoventilation. The causes for this alveolar hypoventilation and its associated physiologic right-to-left shunt include (a) excessive sedation from the premedication, (b) chronic obstructive lung disease or other pulmonary parenchymal disease, and (c) pulmonary congestion/edema secondary to the patient's cardiac disease. Alveolar hypoventilation associated with each of these problems is exacerbated by the supine position of the patient during the catheterization procedure. Helping the patient to assume a more upright posture (head-up tilt or propping the patient up with a large wedge if tilt mechanism is not available) and encouraging the patient to take deep breaths and to cough will correct or substantially ameliorate arterial hypoxemia in most cases. If arterial desaturation persists, oxygen should be administered by face mask for both therapeutic and diagnostic purposes. If full arterial blood oxygen saturation cannot be achieved by face-mask administration of oxygen (it is best in this regard to use a rebreathing mask that fits snugly), a right-to-left shunt is presumed to be present, and its anatomic site and magnitude should be determined using the methods described later in this chapter.

2. Conversely, when the oxygen content of blood in the pulmonary artery is unexpectedly high (i.e., if the pulmonary artery [PA] blood oxygen saturation is >80%), the possibility of a left-to-right intracardiac shunt should be considered. It is for these two reasons that arterial and pulmonary artery saturation should be measured routinely during cardiac catheterization.

3. When the data obtained at cardiac catheterization do not confirm the presence of a suspected lesion, one should consider the presence of an intracardiac shunt. For example, if left ventricular cineangiography fails to reveal mitral regurgitation in a patient in whom this was judged to be the cause of a systolic murmur, it is prudent to look for evidence of a ventricular septal defect (VSD) with left-to-right shunting.

DETECTION OF LEFT-TO-RIGHT INTRACARDIAC SHUNTS

Many techniques are available for the detection, localization, and quantification of left-to-right intracardiac shunts. The techniques vary in their sensitivity, the type of indicator they use, and the equipment needed to sense and read out the presence of the indicator.

Measurement of Blood Oxygen Saturation and Content in the Right Heart (Oximetry Run)

In the oximetry run, a basic technique for detecting and quantifying left-to-right shunts, the oxygen content or percentage saturation is measured in blood samples drawn sequentially
from the pulmonary artery, right ventricle (RV), right atrium (RA), superior vena cava (SVC), and inferior vena cava (IVC). A left-to-right shunt may be detected and localized if a significant step-up in blood oxygen saturation or content is found in one of the right heart chambers. A significant step-up is defined as an increase in blood oxygen content or saturation that exceeds the normal variability that might be observed if multiple samples were drawn from that cardiac chamber.

The technique of the oximetry run is based on the pioneering studies of Dexter and his associates in 1947. They found that multiple samples drawn from the right atrium could vary in oxygen content by as much as 2 volumes percent (vol%). This variability has been attributed to the fact that the right atrium receives its blood from three sources with varying oxygen content: the superior vena cava, inferior vena cava, and coronary sinus. The maximal normal variation within the right ventricle was found to be 1 vol%. Because of more adequate mixing, a maximal variation within the pulmonary artery of only 0.5 vol% was found by Dexter. Thus, using the Dexter criteria, a significant step-up is present at the atrial level when the highest oxygen content in blood samples drawn from the right atrium exceeds the highest content in the venae cavae by 2 vol%. Similarly, a significant step-up at the ventricular level is present if the highest oxygen content in the right ventricular samples is 1 vol% higher than that in the highest right atrial sample, and a significant step-up at the level of the pulmonary artery is present if the pulmonary artery oxygen content is more than 0.5 vol% higher than the highest right ventricular sample.

Dexter’s study described normal variability and gave the criteria for a significant oxygen step-up only for measurement of blood oxygen content. This in part reflects the methodology available to him, because spectrophotometric oximetry was not widely used at that time. In recent years, nearly all cardiac catheterization laboratories (especially those primarily involved in pediatric catheterization) have moved toward the measurement of percentage oxygen saturation by spectrophotometric oximetry as the routine method for oximetric analysis of blood samples. Oxygen content may then be calculated from knowledge of percentage saturation, the patient’s blood hemoglobin concentration, and an assumed constant value for the oxygen-carrying capacity of hemoglobin (1.36 mL O₂/g hemoglobin), as discussed in Chapter 11. When oxygen content is derived in this manner, rather than by measurement by the Van Slyke or other direct oximetric technique, the value is no more accurate (and probably less so because of the potential presence of carboxyhemoglobin or hemoglobin variants with O₂-carrying capacity other than 1.36) than the percentage oxygen saturation values from which it is calculated.

To clarify this situation, Antman and coworkers prospectively studied the normal variation of both oxygen content and oxygen saturation of blood in the right heart chambers. The study population consisted of patients without intracardiac shunts who were undergoing diagnostic cardiac catheterization for evaluation of coronary artery disease, valvular heart disease, cardiomyopathy, or possible pulmonary embolism. Each patient had a complete right heart oximetry run (see later discussion) with sampling of multiple sites in each chamber. Oxygen content was measured directly by an electrochemical fuel cell method (Lex-O₂-Con, Lexington Instruments, Lexington, MA), a method that had been previously validated against the Van Slyke method. Oxygen saturation was calculated as blood oxygen content divided by oxygen-carrying capacity. The relationship between oxygen content and oxygen saturation obviously depends on the hemoglobin concentration in the patient’s blood (e.g., 75% oxygen saturation of pulmonary artery blood will be associated with a substantially lower oxygen content in an anemic patient than in one with normal hemoglobin concentration). Also, systemic blood flow may be an important determinant of oxygen variability in the right heart chambers because high systemic flow tends to equalize the differences across various tissue beds.

In the context of these considerations, listed in Table 12.1 are the criteria for a significant step-up in right heart oxygen content and percentage oxygen saturation associated with various types of left-to-right shunt, based on the study of Antman and coworkers and other investigators. As can be seen from the bottom line (“Any level”) of Table 12.1, the simplest way to screen for a left-to-right shunt is to sample SVC and PA blood and measure the difference, if any, in percentage O₂ saturation. It is recommended that blood samples from SVC and PA be routinely obtained at the time of right heart catheterization and their O₂ saturation determined by reflectance oximetry. If the ΔO₂ saturation between these samples is ≥8%, a left-to-right shunt may be present at atrial, ventricular, or great vessel level, and a full oximetry run should be done.

### Oximetry Run

The blood samples needed to localize a step-up in the right heart are obtained by performing what is called an oximetry run. The samples needed and the recommended order in which they should be obtained follow.

Obtain a 2 mL sample from each of the following locations:

1. Left and/or right pulmonary artery
2. Main pulmonary artery
3. Right ventricle, outflow tract
4. Right ventricle, mid
5. Right ventricle, tricuspid valve or apex
6. Right atrium, low or near tricuspid valve
7. Right atrium, mid
8. Right atrium, high

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*a vol% = 1 mL O₂/100 mL blood, or 10 mL O₂/L of blood.

*b Confirm location by pressure measurement.

1 If frequent extrasystoles occur, do not persist. Obtain samples from three different locations in right ventricle and right atrium.
Table 12.1 Detection of Left-to-Right Shunt by Oximetry

<table>
<thead>
<tr>
<th>Level of Shunt</th>
<th>Criteria for Significant Step-Up</th>
<th>Possible Causes of Step-Up</th>
</tr>
</thead>
<tbody>
<tr>
<td>Atrial (SVC/IVC to RA)</td>
<td>Mean of Distal Chamber Samples: ( O_2 \text{ %sat} \geq 7 )</td>
<td>Atrial septal defect; partial anomalous pulmonary venous drainage; ruptured sinus of Valsalva; VSD with TR; coronary fistula to RA</td>
</tr>
<tr>
<td></td>
<td>Mean of Proximal Chamber Samples: ( O_2 \text{ vol%} \geq 1.3 )</td>
<td>1.5–1.9</td>
</tr>
<tr>
<td></td>
<td>Highest Value in Proximal Chamber: ( O_2 \text{ %sat} \geq 11 )</td>
<td>VSD; PDA with PR; primum ASD; coronary fistula to RV</td>
</tr>
<tr>
<td></td>
<td>Highest Value in Distal Chamber: ( O_2 \text{ vol%} \geq 2.0 )</td>
<td>1.3–1.5</td>
</tr>
</tbody>
</table>

| Ventricular (RA to RV) | Mean of Distal Chamber Samples: \( O_2 \text{ %sat} \geq 5 \) | PDA; aorta-pulmonic window; aberrant coronary artery origin |
|                        | Mean of Proximal Chamber Samples: \( O_2 \text{ vol%} \geq 1.0 \)                      | 1.3–1.3 |
|                        | Highest Value in Proximal Chamber: \( O_2 \text{ %sat} \geq 10 \)                      | |
|                        | Highest Value in Distal Chamber: \( O_2 \text{ vol%} \geq 1.7 \)                      | |

| Great Vessel (RV to PA) | Mean of Distal Chamber Samples: \( O_2 \text{ %sat} \geq 5 \) | All of the above |
|                        | Mean of Proximal Chamber Samples: \( O_2 \text{ vol%} \geq 1.0 \)                      | |
|                        | Highest Value in Proximal Chamber: \( O_2 \text{ %sat} \geq 5 \)                      | |
|                        | Highest Value in Distal Chamber: \( O_2 \text{ vol%} \geq 1.0 \)                      | |

| Any level (SVC to PA) | Mean of Distal Chamber Samples: \( O_2 \text{ %sat} \geq 7 \) | |
|                       | Mean of Proximal Chamber Samples: \( O_2 \text{ vol%} \geq 1.3 \)                      | |
|                       | Highest Value in Proximal Chamber: \( O_2 \text{ %sat} \geq 8 \)                      | |
|                       | Highest Value in Distal Chamber: \( O_2 \text{ vol%} \geq 1.5 \)                      | |

SVC and IVC, superior and inferior vena cavae; RA, right atrium; RV, right ventricle; PA, pulmonary artery; VSD, ventricular septal defect; TR, tricuspid regurgitation; PDA, patent ductus arteriosus; PR, pulmonic regurgitation; ASD, atrial septal defect; SBFI, systemic blood flow index; \( Q_p/Q_s \), pulmonary to systemic flow ratio.

9. Superior vena cava, low (near junction with right atrium)
10. Superior vena cava, high (near junction with innominate vein)
11. Inferior vena cava, high (just at or below diaphragm)
12. Inferior vena cava, low (at L4–L5)
13. Left ventricle
14. Aorta (distal to insertion of ductus)

In performing the oximetry run, an end-hole catheter (e.g., Swan-Ganz balloon flotation catheter) or one with side holes close to its tip (e.g., a Goodale-Lubin catheter) is positioned in the right or left pulmonary artery. Cardiac output is measured by the Fick method. As soon as the determination of oxygen consumption is completed, the operator begins to obtain 2 mL blood samples from each of the locations indicated. This is done under fluoroscopic control, with catheter tip position further confirmed by pressure measurement at the sites noted. The entire procedure should take less than 7 minutes. If a sample cannot be obtained from a specific site because of ventricular premature beats, that site should be skipped until the rest of the run has been completed.

Oxygen saturation and/or content in each of the samples is determined as discussed previously, and the presence and localization of a significant step-up are determined by applying the criteria listed in Table 12.1.

An alternative method for performing the oximetry run is to withdraw a fiberoptic catheter from the pulmonary artery through the right heart chambers and the inferior and superior venae cavae. This permits a continuous readout of oxygen saturation that allows detection of a step-up in oxygen content.
If the oximetry run reveals that a significant step-up is present, the pulmonary blood flow, systemic blood flow, and magnitude of left-to-right and right-to-left shunts may be calculated according to the following formulas.

**Calculation of Pulmonary Blood Flow \( (Q_p) \)**

Pulmonary blood flow is calculated by the same formula used in the standard Fick equation:

\[
Q_p = \frac{O_2 \text{ consumption (mL/min)}}{PA \text{ O}_2 \text{ content (mL/L)} - PV \text{ O}_2 \text{ content (mL/L)}}
\]  \(12.1\)

If a pulmonary vein (PV) has not been entered, systemic arterial oxygen content may be used in the preceding formula, if systemic arterial oxygen saturation is ≥95%. If systemic oxygen saturation is <95%, one must determine whether a right-to-left intracardiac shunt is present. If there is an intracardiac right-to-left shunt, an assumed value of 98% oxygen capacity for the pulmonary venous oxygen content should be used in calculating pulmonary blood flow. If arterial desaturation is present and is not owing to a right-to-left intracardiac shunt, the observed systemic arterial oxygen saturation should be used to calculate pulmonary blood flow.

**Example**

Let us suppose that a patient is found to have an atrial septal defect (ASD) with a left-to-right shunt clearly detected by oximetry run. Furthermore, the catheter crosses the defect and a pulmonary vein is entered, from which a blood sample shows O₂ saturation of 98%. Let us further suppose that systemic arterial blood saturation, however, is 90% and that this is owing to chronic pulmonary disease. After ruling out a right-to-left shunt by any of the various methods (e.g., inhalation of 100% oxygen, indocyanine green dye injection in inferior vena cava, echocardiogram-bubble study), should we use 98% or 90% for pulmonary venous blood O₂ saturation in the calculation of \(Q_p\)? As indicated earlier, because arterial desaturation is not caused by a right-to-left intracardiac shunt, the observed systemic arterial O₂ saturation (90%) should be used because this summates all the pulmonary veins draining both lungs, not just the one with 98% O₂ saturation.

**Calculation of Systemic Blood Flow \( (Q_s) \)**

Use the following equation for systemic blood flow:

\[
Q_s = \frac{O_2 \text{ consumption (mL/min)}}{SA \text{ O}_2 \text{ content (mL/L)} - MV \text{ O}_2 \text{ content (mL/L)}}
\]  \(12.2\)

The key to proper measurement of systemic blood flow in the presence of an intracardiac shunt is that the mixed venous oxygen content must be measured in the chamber immediately proximal to the shunt, as shown in Table 12.2.

The formula generally used by cardiologists who treat adults for the calculation of venous content in the presence of an ASD was derived by Flamm and coworkers. They found that systemic blood flow calculated from mixed venous oxygen content as determined from the formula listed in Table 12.2 most closely approximates systemic blood flow as measured by left ventricular to brachial artery (BA) dye curves in patients with atrial septal defect studied at rest. It should be noted that Flamm’s formula weights blood returning from the superior vena cava more heavily than might be expected on the basis of relative flows in the superior and inferior cavae. The success of this empirical weighting of the relatively desaturated superior vena cava blood (O₂ saturation is almost always less in blood from the superior as opposed to the inferior vena cava) probably reflects the fact that the third contributor to mixed venous blood—desaturated coronary sinus blood—is not sampled during the oximetry run and therefore cannot be included directly in the formula. The formula \((3 \text{ SVC } O_2 \text{ content} + 1 \text{ IVC } O_2 \text{ content})/4\) was validated by Flamm and associates for mixed venous oxygen content at rest: In 18 patients without shunt, this value agreed closely with pulmonary artery

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**Table 12.2** Calculation of Systemic Blood Flow in the Presence of Left-to-Right Shunt

<table>
<thead>
<tr>
<th>Location of Shunt as Determined by Site of O₂ Step-Up</th>
<th>Mixed Venous Sample to be Used in Calculating Systemic Blood Flow</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Pulmonary artery (e.g., patent ductus arteriosus)</td>
<td>Right ventricle, average of samples obtained during oximetry run</td>
</tr>
<tr>
<td>2. Right ventricle (e.g., ventricular septal defect)</td>
<td>Right atrium, average of all samples during oximetry run</td>
</tr>
<tr>
<td>3. Right atrium (e.g., atrial septal defect)</td>
<td>(3(\text{SVC } O_2 \text{ content}) + 1(\text{IVC } O_2 \text{ content})/4)</td>
</tr>
</tbody>
</table>
blood oxygen content at rest. During supine bicycle exercise, however, a different relationship was found to apply, in which mixed venous (pulmonary artery) oxygen content in patients without shunt was best approximated as \(1 \text{ SVC } O_2 + 2 \text{ IVC } O_2/3\). This formula was then used for patients with atrial septal defect during exercise, and it reliably predicted systemic blood flow measured by left ventricular to BA dye-dilution curve. Therefore, for patients with left-to-right shunt at the atrial level, the formula in Table 12.2 should be used only for calculation of resting mixed venous \(O_2\) content.

Obviously, calculations based on the formula in Table 12.2 would be changed a little in many cases by ignoring inferior vena cava blood altogether, and this is done in some laboratories (especially those involved in pediatric catheterization). Flamm and associates, however, examined the effects of assuming that superior vena cava \(O_2\) content equaled mixed venous \(O_2\) content and concluded that this method was somewhat less accurate (both in the 18 subjects without shunt and in the 9 patients with atrial septal defect and left-to-right shunt) than the formula given in Table 12.2.\(^3\)

### Calculation of Left-to-Right Shunt

If there is no evidence of an associated right-to-left shunt, the left-to-right shunt is calculated by

\[
L \rightarrow R \text{ shunt} = Q_p - Q_s \text{(measured in L/min)} \tag{12.3}
\]

### Examples of Left-to-Right Shunt Detection and Quantification

Some examples of oximetry runs are presented to illustrate interpretation.

### Atrial Septal Defect

In the example seen in Figure 12.1, there is a step-up in oxygen saturation in the mid–right atrium. The average or mean value for the vena caval samples in this patient is calculated as \((3[\text{SVC}] + 1[\text{IVC}]) / 4. \text{ SVC}\) is the average of SVC samples (i.e., 67.5% in this example), and \(\text{IVC}\) is the value for the IVC sample taken at the level of the diaphragm only (i.e., 73%). Thus the vena caval mean \(O_2\) saturation for the example illustrated in Figure 12.1 is \((3[67.5] + 1[73]) / 4 = 69\%\). The right atrial mean \(O_2\) saturation for this patient is \((74 + 84 + 79 + 73) / 4 = 79\%\). The 10% step-up in mean \(O_2\) saturation from vena cava to right atrium is higher than the 7% value listed in Table 12.1 as a criterion for a significant step-up at the atrial level. Note that for this example, the highest-to-highest approach (highest right atrial \(O_2\) saturation to highest vena caval \(O_2\) saturation) would barely meet the criteria for a significant step-up, because of the high value of IVC saturation (73%) as compared with SVC saturation. Thus for the detection of a significant step-up at the atrial level using the highest-to-highest approach, it is better to use the highest RA and SVC samples. In this case, the result would be \((84\% - 68\%) = 16\%\), which is clearly above the 11% value listed in Table 12.1 for detection of a significant step-up. Also, the screening samples that we recommend for all right heart catheterizations (a single sample each from SVC and PA) would have strongly indicated a shunt at some level in the right heart, since \(\Delta O_2\) saturation from SVC to PA is 12% to 13%, well above the 8% value for a significant step-up.

To calculate pulmonary and systemic blood flows for the example given in Figure 12.1, we need to know \(O_2\) consumption and blood \(O_2\) capacity. If the patient's \(O_2\) consumption is 240 mL \(O_2/\text{minute}\) and the blood hemoglobin concentration is 14 g%, pulmonary and systemic blood flows may be calculated as follows:

\[
Q_p = \frac{\text{PV } O_2 \text{ consumption (mL/min)}}{\text{PV } O_2 \text{ content (mL/L)}} - \frac{\text{PA } O_2 \text{ content (mL/L)}}{14 \text{ g Hgb/100 mL blood} \times \frac{1.36 \text{ mL } O_2}{\text{g Hgb}}} \tag{12.4}
\]

PV \(O_2\) content was not measured, but left ventricular (LV) and arterial blood \(O_2\) saturation was 96% (effectively ruling out a right-to-left shunt), and therefore it may be assumed that PV \(O_2\) saturation was 96%. As described in Chapter 11, oxygen content of PV blood is calculated as follows:

\[
0.96 \left( \frac{14 \text{ g Hgb}}{100 \text{ mL blood}} \right) \times \left( \frac{1.36 \text{ mL } O_2}{\text{g Hgb}} \right) = 18.3 \text{ mL } O_2/100 \text{ mL blood} \tag{12.5}
\]
Similarly, PA $O_2$ content is calculated as

$$0.80(14)1.36 \times 10 = 152 \text{ mL } O_2/\text{liter}$$

(12.6)

Therefore,

$$Q_p = \frac{240 \text{ mL } O_2/\text{min}}{[183 - 152] \text{ mL } O_2/L}$$

$$= 7.74 \text{ L/min}$$

(12.7)

Systemic blood flow for the example illustrated in Figure 12.1 is calculated as

$$Q_s = \frac{240 \text{ mL } O_2/\text{min}}{\text{(systemic arterial } O_2 \text{ content) - (mixed venous } O_2 \text{ content)}}}$$

$$= \frac{240}{(0.96 - 0.69) 14(1.36) 10}$$

$$= 4.7 \text{ L/min}$$

For this calculation, mixed venous $O_2$ saturation was derived from the formula given in Table 12.2 as 69%. Thus the ratio of $Q_p/Q_s$ in this example is $7.74/4.7 = 1.65$, and the magnitude of the left-to-right shunt is $7.7 - 4.7 = 3$ L/min. This patient has a small to moderate atrial septal defect.

**Ventricular Septal Defect**

Figure 12.2 shows another example of findings in an oximetry run. In this case, the patient has a large $O_2$ step-up in the right ventricle, indicating the presence of a ventricular septal defect. If $O_2$ consumption is 260 mL/minute and hemoglobin is 15 g%, then

$$Q_r = \frac{260}{(0.97 - 0.885) 15(1.36) 10} = 15 \text{ L/minute}$$

$$Q_s = \frac{260}{(0.97 - 0.66) 15(1.36) 10} = 4.1 \text{ L/minute}$$

(12.9)

$$Q_p/Q_s = 15/4.1 = 3.7$$

L → shunt = $15 - 4.1 = 10.9 \text{ L/minute}$

In this case, the $O_2$ saturation of mixed venous blood is calculated by averaging the right atrial $O_2$ saturations because the right atrium is the chamber immediately proximal to the $O_2$ step-up.

**Flow Ratio**

The ratio $Q_p/Q_s$ gives important physiologic information about the magnitude of a left-to-right shunt. In addition, because it factors out other variables (e.g., $O_2$ consumption), the ratio can be calculated from knowledge of blood $O_2$ saturation alone. A $Q_p/Q_s$ ratio of < 1.5 signifies a small left-to-right shunt and is often a motivation to argue against operative correction, particularly if the patient has an otherwise uncomplicated atrial or ventricular septal defect. A ratio of ≥ 2.0 indicates a large left-to-right shunt and is generally considered sufficient evidence to recommend surgical repair of the defect, to prevent late pulmonary vascular disease as well as other complications of prolonged circulatory overload. Flow ratios between 1.5 and 2.0 are obviously intermediate in magnitude; surgical correction is generally recommended if operative risk is low. A flow ratio of < 1.0 indicates a net right-to-left shunt and is often a sign of the presence of irreversible pulmonary vascular disease.

A simplified formula for the calculation of flow ratio can be derived by combining the equations for systemic and pulmonary blood flow to obtain

$$\frac{Q_p}{Q_s} = \frac{\text{SA } O_2 - \text{MV } O_2}{\text{PV } O_2 - \text{PA } O_2}$$

(12.10)

where SA $O_2$, MV $O_2$, PV $O_2$, and PA $O_2$ are systemic arterial, mixed venous, pulmonary venous, and pulmonary arterial blood oxygen saturations, respectively. For the case illustrated in Figure 12.1,

$$\frac{Q_p}{Q_s} = (96\% - 69%)/(96\% - 80\%) = 1.69.$$
effective blood flow, the flow that would exist in the absence of any left-to-right or right-to-left shunting:

\[ Q_{\text{eff}} = \frac{O_2 \text{ consumption (mL/min)}}{\left(\frac{\text{PV } O_2 \text{ content (mL/L)}}{-\text{MV } O_2 \text{ content (mL/L)}}\right)} \]  

(12.11)

The approximate left-to-right shunt then equals \( Q_{p} - Q_{\text{eff}} \), and the approximate right-to-left shunt equals \( Q_{s} - Q_{\text{eff}} \). Actually, this effective blood flow approach is an approximation of the significantly more complex formula shown in Eq. (12.12).

**Limitations of the Oximetry Method**

There are several limitations and potential sources of error in the calculation of blood flow using the data obtained from an oximetry run. A primary source of error may be the absence of a steady state during the collection of blood samples. That is, if the oximetry run is prolonged because of technical difficulties, if the patient is agitated, or if arrhythmias occur during the oximetry run, the data may not be consistent.

An important limitation of the oxygen step-up method for detecting intracardiac shunts is that it lacks sensitivity. Most shunts of a magnitude that would lead to a recommendation for surgical closure of a ventricular septal defect or patent ductus arteriosus are detected by this method. Small shunts, however, are not consistently detected by this technique.

As pointed out by Antman and coworkers, the normal variability of blood oxygen saturation in the right heart chambers is strongly influenced by the magnitude of systemic blood flow. High levels of systemic flow tend to equalize the arterial and venous oxygen values across a given vascular bed. Therefore, elevated systemic blood flow will cause the mixed venous oxygen saturation to be higher than normal, and interchamber variability owing to streaming will be blunted. Even a small increase in right heart oxygen saturation under such conditions might indicate the presence of a significant left-to-right shunt; larger increases would indicate voluminous left-to-right shunting of blood. For a patient with a systemic blood flow index of 3.0 L/minute per M², minimum shunt sizes that could be detected reliably by oximetry are listed in Table 12.1.

Fundamental to the oximetric method of shunt detection is the fact that left-to-right shunting across an intracardiac defect will cause an increase in blood O₂ saturation in the chamber receiving the shunt proportional to the magnitude of the shunt. The increase in blood O₂ content in the chamber receiving the shunt, however, depends not only on the magnitude of the shunt but also on the O₂-carrying capacity of the blood (i.e., the hemoglobin concentration). As reported by Antman and colleagues, the influence of blood hemoglobin concentration may be important when blood O₂ content (rather than O₂ saturation) is used to detect a shunt (Table 12.3).

Thus, the same shunt giving the same blood O₂ saturation step-up would give markedly different blood O₂ content step-ups if the blood hemoglobin concentration varied significantly. Accordingly, when evaluating oximetric data for shunt detection, it is a more precise method to exclude the potential influence of blood O₂-carrying capacity and use only O₂ saturation data. This is especially true in pediatric cases where the normal blood O₂-carrying capacity may vary from 20 to 28 vol% in the neonate to 12 to 16 vol% in infancy. To minimize errors and maximize the physiologic strengths of the oximetry method for shunt detection and quantification, the guidelines listed in Table 12.4 should be followed.

### Table 12.3

<table>
<thead>
<tr>
<th>Hemoglobin Concentration (vol%)</th>
<th>(g/100 mL)</th>
<th>Increase in O₂ Saturation (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>10</td>
<td>12</td>
</tr>
<tr>
<td>5</td>
<td>0.68</td>
<td>0.82</td>
</tr>
<tr>
<td>10</td>
<td>1.36</td>
<td>1.63</td>
</tr>
<tr>
<td>15</td>
<td>2.04</td>
<td>2.45</td>
</tr>
<tr>
<td>20</td>
<td>2.72</td>
<td>3.26</td>
</tr>
</tbody>
</table>


**Other Indicators**

Many other more sensitive techniques are available for detecting smaller left-to-right shunts. These include indocyanine green dye curves, radionuclide techniques, contrast angiography, and echocardiographic methods. Some of these
methods (e.g., green dye) were discussed extensively in previous editions of this textbook, and the interested reader is referred there for details. For discussion of other predominantly non-catheter-based methods (e.g., echo, radionuclide) the reader is referred to textbooks devoted to those techniques. We will give only one example here of one of the older methods.

**Early Recirculation of an Indicator**

Standard indicator-dilution curves method, performed by injection of indocyanine green into the pulmonary artery with sampling in a systemic artery, is rarely used today, and most laboratories are not even equipped to perform this technique. In the presence of a left-to-right shunt, however, a green dye curve produced by this technique will demonstrate early recirculation on the downslope of the dye curve7 (Figure 12.3).

This technique can detect left-to-right shunts too small to be detected by the oxygen step-up method.8 Thus if there is no evidence of a left-to-right shunt by this method, there is no need to perform an oximetry run. The studies of Castillo and coworkers9 suggest that left-to-right shunts as small as 25% of the systemic output can be detected by standard pulmonary artery to systemic artery dye curves.

Although a simple pulmonary to systemic artery indocyanine green dye curve may detect the presence of a shunt, it does not localize it. That is, a pulmonary artery to systemic artery dye curve will show evidence of early recirculation in the presence of a left-to-right shunt owing to an atrial septal defect, ventricular septal defect, or patent ductus arteriosus.

**Angiography**

Selective angiography is effective in visualizing and localizing the site of left-to-right shunts. Angiographic demonstration of anatomy has become a routine part of the preoperative evaluation of patients with congenital or acquired shunts and is useful in localizing the anatomic site of the shunt. Actually, the use of angiography in this fashion should be considered an indicator-dilution method, with the radiographic contrast agent being the indicator and the cinellufluoroscopy unit serving as the densitometer.

In general, assessment of the patient with a left-to-right shunt virtually always includes a left ventriculogram. If this is performed in the left anterior oblique projection with cranial angulation (or done as a biplane study with both left and right anterior oblique views), excellent visualization of the interventricular septum, sinuses of Valsalva, and ascending and descending thoracic aorta will allow diagnosis and localization of essentially all the causes of left-to-right shunt other than atrial septal defect and anomalous pulmonary venous return.

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1. Blood samples at multiple sites should be obtained rapidly.
2. Blood $O_2$ saturation data rather than $O_2$ content data are preferable to identify the presence and location of a shunt.
3. Comparison of the mean of all values obtained in the respective chambers is preferable to comparison of the highest values in each chamber.
4. Because of the significant influence of systemic blood flow on shunt detection, exercise should be used in equivocal cases where a low systemic blood flow is present at rest.

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Guidelines for Optimum Use of the Oximetric Method for Shunt Detection and Quantification


If pulmonary vein is not entered, use 98% × $O_2$ capacity.
Complicated lesions (e.g., endocardial cushion defects, coronary artery/right heart fistulas, ruptured aneurysms at the sinus of Valsalva) commonly require angiographic delineation before surgical intervention can be undertaken. Angiography also helps to assess the “routine” cases more completely. For instance, does the patient with secundum atrial septal defect have associated left ventricular dysfunction or mitral valve prolapse? Does the patient with ventricular septal defect have associated aortic regurgitation (caused by prolapse of the medial aortic leaflet) or infundibular pulmonic stenosis?

Angiography, however, cannot replace the important physiologic measurements that allow quantitation of flow and vascular resistance. Without quantitative evaluation of pulmonary and systemic flows (Qp and Qs) and their associated resistances (PVR and SVR), appropriate decisions regarding patient management cannot be made, nor can prognosis be assessed.

**DETECTION OF RIGHT-TO-LEFT INTRACARDIAC SHUNTS**

The primary indication for the use of techniques to detect and localize right-to-left intracardiac shunts is the presence of cyanosis or, more commonly, arterial hypoxemia. The presence of arterial hypoxemia raises two specific questions: first, is the observed hypoxemia owing to an intracardiac shunt, or is it owing to a ventilation/perfusion imbalance secondary to a variety of forms of intrinsic pulmonary disease? This problem is particularly important in patients with coexistent congenital heart disease and pulmonary disease. Second, if hypoxemia is caused by an intracardiac shunt, what is its site and what is its magnitude?

Attempts to measure right-to-left shunts in patients with cyanotic heart disease date back at least to 1941.20-23 Prinzmetal,20 in a series of ingenious experiments, expanded the earlier observation of Benenson and Hitzig that ether injected intravenously in patients with cyanotic heart disease will cause a prickle, burning sensation of the face.16 This sensation is caused by the entry of ether into the systemic circulation of patients with right-to-left shunts. In normal subjects without right-to-left shunts, the ether is eliminated by the lungs and thus does not reach the systemic circulation. Prinzmetal then measured the time necessary for an intravenous injection of a dilute solution of saccharin to be tasted. This time is equal to the transit time from a peripheral vein through the lungs, through the left heart, and then to the systemic circulation. By increasing the concentration of saccharin, he found that a second, much shorter appearance time occurred in patients with cyanotic heart disease because of the presence of a right-to-left shunt bypassing the pulmonary circulation. He then estimated the percent right-to-left shunt by the following formula:

\[
\% \text{ R } \rightarrow \text{ L Shunt} = \frac{A}{A + C} \quad (12.13)
\]

where \( A \) is the smallest concentration of saccharin to be tasted by way of the long circuit and \( C \) is the smallest concentration of saccharin to be tasted by way of the short circuit.

Our current methods of documenting and quantitating right-to-left shunts may not be as ingenious and certainly are not as sweet, but they are nonetheless effective.

**Angiography**

With appropriate techniques, angiography may be used to detect right-to-left intracardiac shunts. This method is particularly important in detecting right-to-left shunting caused by a pulmonary arteriovenous fistula. In this circumstance, the shunt cannot be detected by indicator-dilution curves on the basis of a shortened appearance time. That is, the difference in transit time when the pulmonary capillaries are bypassed is not perceptible by standard indicator-dilution techniques. Although angiography may localize right-to-left shunts, it does not permit quantification.

**Oximetry**

The site of right-to-left shunts may be localized if blood samples can be obtained from a pulmonary vein, the left atrium, left ventricle, and aorta. The pulmonary venous blood of patients with arterial hypoxemia caused by an intracardiac right-to-left shunt is fully saturated with oxygen. Therefore, the site of a right-to-left shunt may be localized by noting which left heart chamber is the first to show desaturation (i.e., a step-down in oxygen concentration). Thus if left atrial blood oxygen saturation is normal but desaturation is present in the left ventricle and in the systemic circulation, the right-to-left shunt is across a ventricular septal defect. The only disadvantage of this technique is that a pulmonary vein and the left atrium must be entered. This is not as easy in adults as it is in infants, in whom the left atrium may be entered routinely by way of the foramen ovale.

**Echocardiography**

Echocardiographic methods have been proved sensitive enough for the detection and localization of left-to-right and right-to-left shunts. The so-called echocardiographic contrast or “bubble study” using agitated saline solution with microbubbles or some of the newer specifically designed echo contrast agents can detect small shunts, and the use of two-dimensional echocardiographic techniques can usually localize the site of the shunt to the atrial or ventricular septum. Combined echocardiographic and cardiac catheterization studies involve injection of the echo contrast agent into the right or left heart chambers sequentially, thus permitting localization of the shunt and determination of whether it is unidirectional or bidirectional. Echo-Doppler techniques can also be used to detect and localize intracardiac shunts. In this regard, color Doppler echocardiography is particularly useful in detecting and localizing small intracardiac shunts without the need for injection of an echo contrast agent. An example of the use of the echo-contrast technique for the detection of an atrial septal defect with left-to-right shunting is shown in Figure 12.4.
Section III Hemodynamic Principles

Two-dimensional echo showing right ventricular (RV) inflow tract (top), short axis views at the base (middle) (AO = aorta), and four-chamber apical view (bottom) in a patient with an atrial septal defect (ASD), shown at cardiac catheterization to be associated with a $Q_p/Q_s$ of 3.0. Left views. The anatomy before echo contrast injection. Following an intravenous injection of agitated saline solution (right views), a negative contrast effect (black arrows) is seen within the right atrium (RA), compatible with entry of unopacified blood from the left atrium (LA) across the ASD into the RA. The ASD is visualized (white arrow) as an area of septal dropout. (Reproduced from Come PC, Riley M. Contrast echocardiography. In: Come PC, ed. Diagnostic Cardiology: Noninvasive Imaging Techniques. Philadelphia, PA: JB Lippincott, 1984:294, with permission.)

REFERENCES

Chapter 12 Shunt Detection and Quantification


