Chapter 14
Intracardiac Shunts

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Introduction and Epidemiology of the Disease State

In the normal circulation, deoxygenated blood comes into the right heart and passes through the pulmonary circulation to become oxygenated. Then oxygenated blood goes through the left heart to the systemic circulation. An abnormal communication between two heart chambers resulting in an intracardiac (IC) shunt may take place from systemic to pulmonary circulation (left to right) or from pulmonary to systemic circulation (right to left) or may be bidirectional.

While congenital heart diseases are the most common causes of intracardiac shunts, acquired pathologies may also result in IC shunts. Left to right (L→R) shunt in post myocardial infarction VSD and right to left (R→L) shunt in platypnea orthodeoxia syndrome (POS) are two examples of acquired IC shunts.

Detection, localization, and quantification of intracardiac shunts are clinically important in the management of IC shunts and can be performed using noninvasive and invasive techniques. Noninvasive techniques include echocardiography, cardiovascular magnetic resonance (CMR), and radionuclide tests. Invasive techniques apply catheter insertion and selective blood sampling for oxygen saturation to diagnose and quantify IC shunts.

Noninvasive Assessment of Intracardiac Shunts

Transthoracic echocardiography (TTE) is a safe, reproducible, and a relatively inexpensive method that is widely used in the assessment of intracardiac shunts. Transesophageal echocardiography (TEE) is an excellent tool for defining the anatomy of IC shunts; however, its incremental value in shunt assessment is limited. Magnetic resonance

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imaging (MRI) allows precise measurement of cardiac volumes and flows yielding accurate IC shunt calculations.

Echocardiographic Assesment of Intracardiac Shunts

Echocardiography has been the primary diagnostic tool and plays an essential role in providing morphologic assessment and hemodynamic evaluation in congenital heart disease. TTE permits comprehensive anatomic information regarding the location and the size of the defect. TEE may be needed as a complimentary imaging tool particularly in lesions located posteriorly and in patients who will undergo percutaneous or surgical intervention. Color flow Doppler plays critical role in detection and localization of IC shunts as well as in determinating direction of shunting. Pulmonary blood flow (Q_p) to systemic blood flow (Q_s) ratio can be easily calculated using Doppler and 2D echocardiography. Contrast echocardiography is another application which enables the demonstration of right to left shunts or bidirectional shunts.

Comprehensive evaluation of a patient with IC shunt is not limited to detection and quantification of the shunt flow. It also involves the evaluation of the associated abnormalities and secondary findings. For example, in a patient with ASD, evaluation of right atrial and right ventricular size and septal motion and for other associated anomalies such as anomalous pulmonary venos return is as important as quantification of the defect.

The hemodynamic significance of intracardiac shunts can be evaluated based on volumetric flow calculations using cross sectional area (CSA) and velocity time integral (VTI) across the outflow tracts of both ventricles. Pulmonary flow (Q_p) equals systemic flow (Q_s) in the absence of shunt. Formulas are used to calculate volumetric flow with two important assumptions. The first assumption is blood flow has a uniform pattern and constant velocity. The second assumption is that the shape of the outflow tract is circular. Flow formula is as follows:

$$Q = \mathrm{CSA} \times \mathrm{VTI}$$

(Q = flow, CSA = Cross sectional area, VTI = Velocity time integral)
CSA is calculated based on circular shape assumption:

$$\mathrm{CSA} = \pi \times \mathrm{r}^2$$

(π = pi constant which is 3.14, r = radius of the outflow tract)
For the pulmonary flow,

$$Q_p = \mathrm{CSARVOT} \times \mathrm{VTIRVOT}$$
$$Q_p = \pi \times (\mathrm{RVOTD}/2)^2 \times \mathrm{VTI\ RVOT}$$
$$Q_p = \pi \times (\mathrm{RVOT_D})^2 / 4 \times \mathrm{VTI_{RVOT}} (\pi / 4 = 0.785)$$
$$Q_p = 0.785 \times \mathrm{RVOTd}^2 \times \mathrm{VTI_{RVOT}}$$

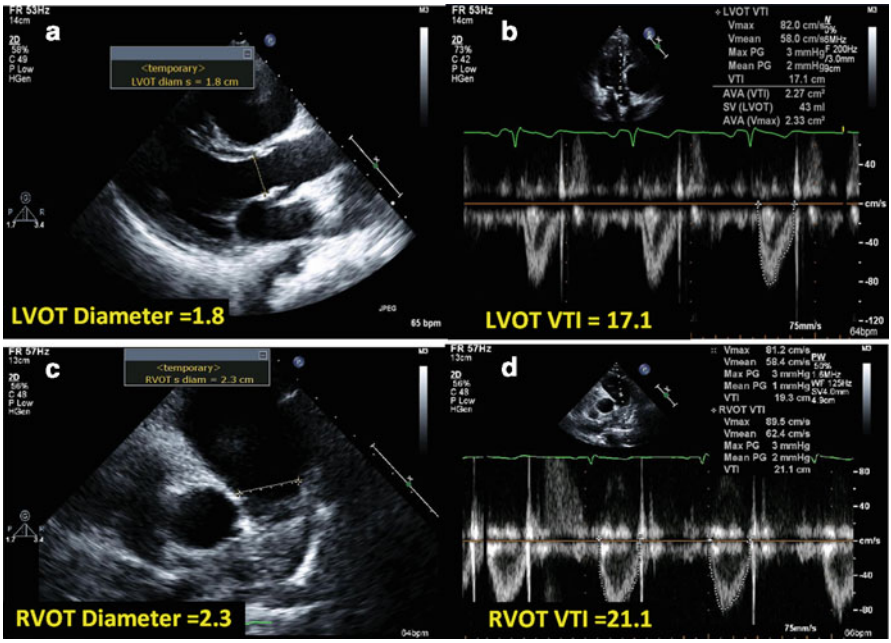


Fig. 14.1 Quantification of IC shunts using transthoracic echocardiography. Systemic stroke volume or flow (Q_s) can be calculated by using CSA of LVOT which is derived by LVOT diameter at the end of systole (**a**) and LVOT VTI (**b**) pulmonary stroke volume or flow (Q_p) can be measured using CSA of RVOT which is derived by RVOT diameter at the end of systole (**c**) and RVOT VTI (**d**)

$$\frac{Q_p}{Q_s} = \frac{\text{CSA of RVOT} \times \text{VTIRVOT}}{\text{CSA of LVOT} \times \text{VTILVOT}} \qquad \frac{Q_p}{Q_s} = \frac{3.14 \times (2.3/2)^2 \times 21.1}{3.14 \times (1.8/2)^2 \times 17.1} \qquad \frac{Q_p}{Q_s} = \frac{87.6}{43.5} = 2$$

CSA cross sectional area; *LVOT* left ventricle outflow tract; *VTI* velocity time integral; and *RVOT* right ventricle outflow tract

For the systemic flow, the formula would be simplified as follow:

$$Q_s = 0.785 \times \text{LVOTd}^2 \times \text{VTI}_{\text{LVOT}}$$

After simplification the formula of Qp/Qs is:

$$\frac{Q_p}{Q_s} = \frac{\text{RVOTd}^2 \times \text{VTIRVOT}}{\text{LVOTd}^2 \times \text{VTILVOT}}$$

See the example in Fig. 14.1. (Q_p = Pulmonary flow; Q_s = Systemic flow; RVOTd^2 = Right ventricle outflow tract diameter; LVOTd^2 = Left ventricle outflow tract diameter).

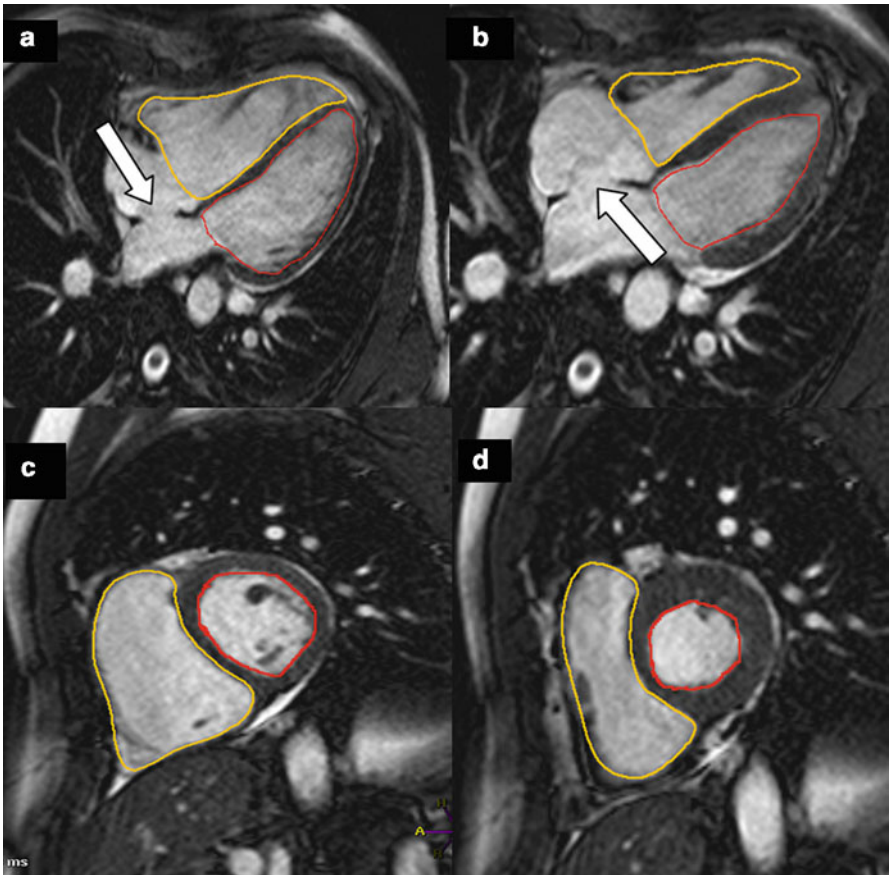


Fig. 14.2 Volumetric method for the quantification of IC shunt. Diastolic (**a**) and systolic (**b**) four chamber cine MR images of both ventricles demonstrate moderately dilated RV with normal systolic function. Diastolic (**c**) and systolic (**d**) short axis cine MR images of both ventricles. The ratio of the RV to LV stroke volumes gives shunt ratio (Q_p/Q_s). LV EDV = 194 cm^3; LV ESV = 102 cm^3; LV SV = 92 cm^3; LV EF = 48%, RV EDV = 289 cm^3; RV ESV = 124 cm^3; RV SV = 165 cm^3; and RV EF = 57%. Shunt ratio can be therefore calculated for this ASD case (*white arrows* show the defect); $Q_p/Q_s = 165/92 = 1.8$ (*ASD* atrial septal defect; *EDV* end diastolic volumes; *ESV* end systolic volumes; *LV* left ventricle; and *RV* right ventricle)

Potential Source of Errors and Pitfalls

Precise measurements of LVOT and RVOT diameters require appropriate site selection. LVOT diameter should be measured at the level of the aortic annulus during systole in parasternal long axis view of the LV, whereas RVOT is measured at the level of pulmonary valve annulus in parasternal short axis view (see Fig. 14.1). It is important to note that CSA is calculated as if it is a perfect circle. CSA of outflow tracts can change throughout cardiac cycle which may cause error. Positioning of sample volume of pulsed wave Doppler signals should be obtained at the levels where RVOT and LVOT diameters were measured.

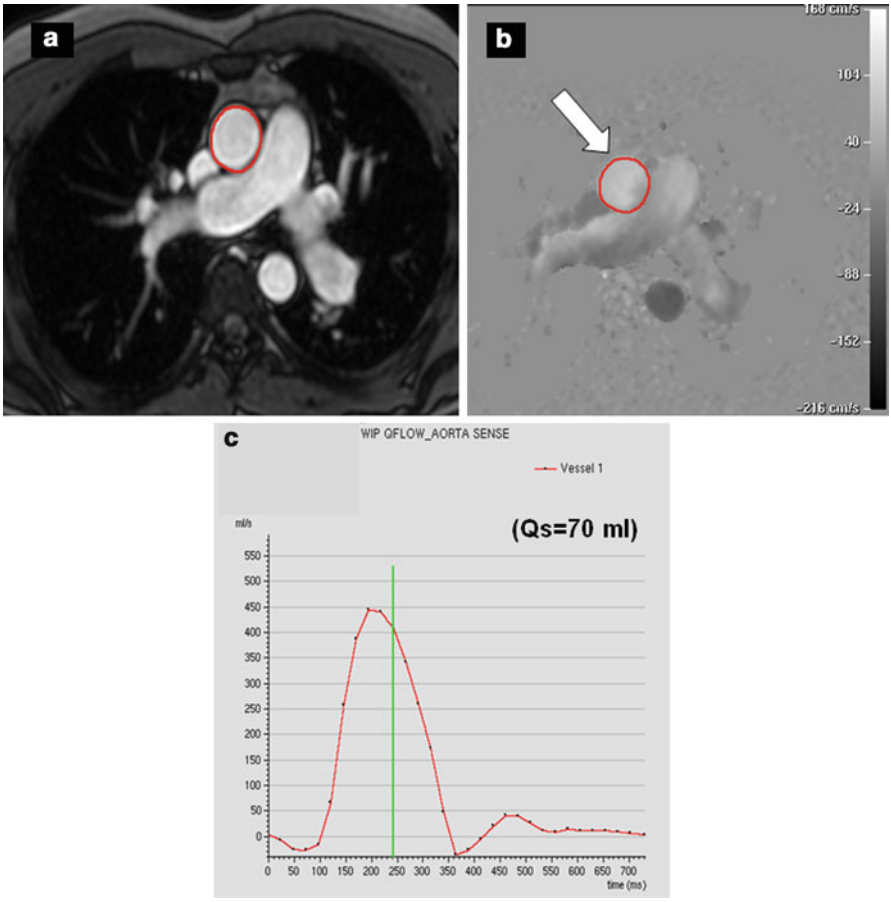


Fig. 14.3 (**a**–**c**) Velocity encoded (phase contrast) cine MR imaging for the quantitation of systemic flow (Q_s) (**a**) Magnitude image of the ascending aorta for the measurement of cross sectional area of the vessel. The plane is positioned at the level of the bifurcation of the main pulmonary artery, (**b**) phase contrast image perpendicular to the ascending aorta (*white arrow*) (**c**) Through-plane velocity mapping creates flow vs. time curves. The area under the curve represents stroke volume of the ascending aorta (Q_s) which was measured 70 mL/beat for this case. ($Q_s = 70$ mL). (**d**–**f**) Phase contrast cine MR imaging for the quantitation of pulmonary flow(Q_p) (**a**) Magnitude image of the main pulmonary artery, (**b**) Phase contrast image perpendicular to the main pulmonary artery (*white arrow*) (**c**) Through-plane velocity mapping demonstrates flow vs. time curves across the main pulmonary artery. The area under the curve represents stroke volume of the pulmonary artery (Q_p) which was calculated 162 mL/beat for this case. The shunt ratio was therefore calculated $Q_p/Q_s = 162/70 = 2.2$, which indicates significant left to right shunting

Optimal Doppler signals must be acquired for accurate velocities and VTI. Respiratory variations can affect position of PW sample location or Doppler velocities.

Many other pitfalls such as arrhythmia, heart rate variability, and presence of valvular heart disease in particular aortic and mitral regurgitation may also complicate

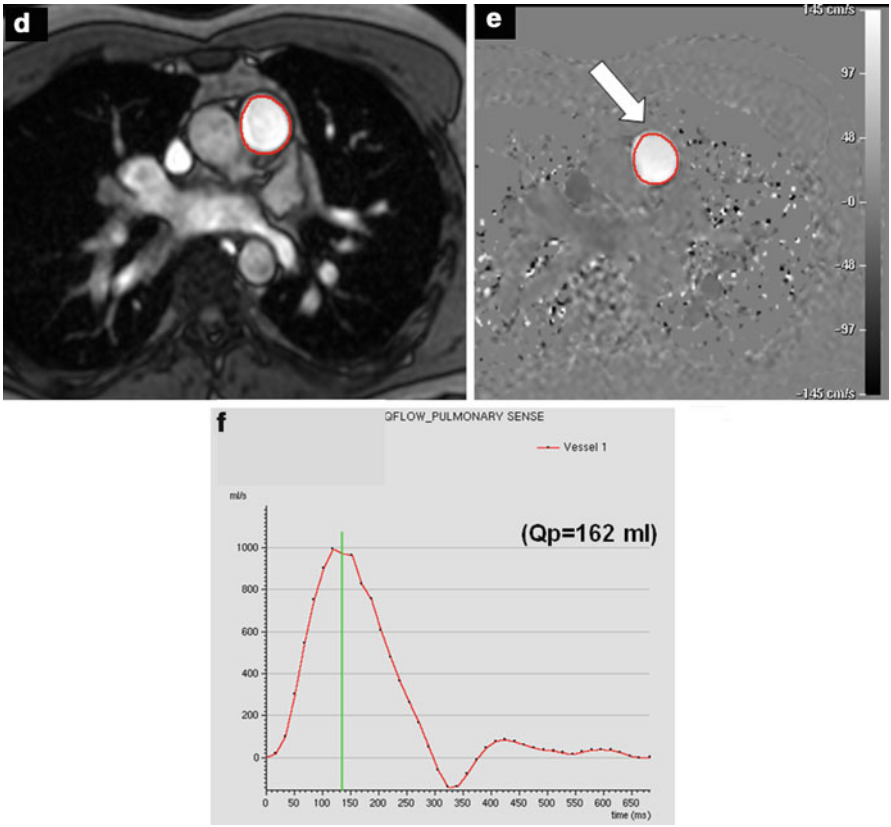


Fig. 14.3 (continued)

shunt assessment. A small error in the diameter measurement is magnified in the calculation of cross sectional area translating into large errors in flow calculations.

Assessment of Intracardiac Shunt with Cardiovascular Magnetic Resonance

Although echocardiography is initial diagnostic tool for the assessment of congenital heart disease (CHD), cardiovascular magnetic resonance (CMR) has become an important technique for the noninvasive evaluation of the size and morphologic features of the congenital cardiac defects. MRI provides not only the exact visual-

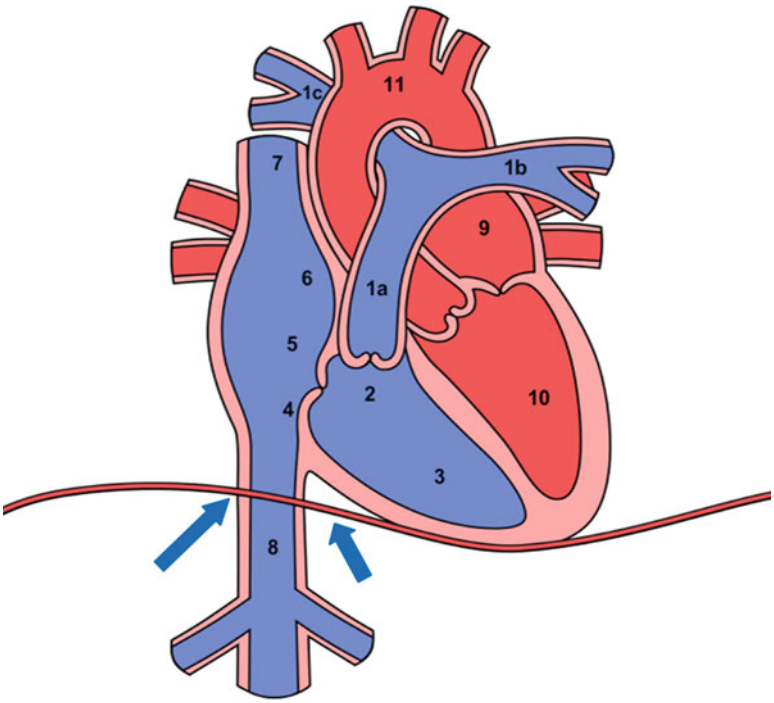


Fig. 14.4 Exact localization for the blood sampling in oxymetric run study. *1a* Main pulmonary artery, *1b* left pulmonary artery, *1c* right pulmonary artery, *2* right ventricular outflow tract, *3* right ventricle, *4* low right atrium, *5* mid right atrium, *6* high right atrium, *7* superior vena cava, *8* inferior vena cava (sample should be obtained just below the diaphragm (*blue arrows*); hepatic vein must be taken into account while obtaining inferior vena cava blood), *9* pulmonary vein, *10* left ventricle, *11* aorta or femoral artery

ization of cardiac anatomy but also allows accurate and reproducible quantification of IC shunts. Studies demonstrated MRI measurements of IC shunts correlate very well with those obtained by invasive methods in children [1–3] as well as in adults [4] using different MRI applications [5, 6]. Volumetric and phase contrast cine MRI are commonly used protocols for the assessment of IC shunt. Ventricular stroke volume can be easily calculated for each ventricle with short axis and/or four chamber views (Fig. 14.2). In the absence of significant valvular regurgitation or ventricular septal defect (VSD), the ratio of the RV to LV stroke volumes yields the Q_p/Q_s ratio. Velocity encoded (VENC) cine MR is another application for the measurement of IC shunt [5]. Each voxel has its own velocity across the vessel in the grey scale images. Flow can be estimated using cross sectional area of the vessel and integrated into the velocity of the blood at the same level. Magnitude images provide an accurate measurement for the cross sectional areas of the vessel and phase cine MR images offer reliable quantification for mean flow velocity [2] (Fig. 14.3a, b).

MRI has many advantages when compared to other noninvasive imaging modalities. Unlike echocardiography, MR allows visualization of vascular

structures in addition to cardiac chambers. It is possible to make reliable and reproducible measurements of blood flow velocities and assess stenotic and regurgitant valvular lesions by CMR. These can be accomplished with much less subjectivity compared with echocardiography. In contrast to radionuclide technique or cardiac computed tomography (CT), MR does not have any ionizing radiation. In addition to accurate quantification of IC shunts, MRI is a promising technique for the guidance of transcatheter closure of congenital heart defects [7]. After closure of such defects, MRI can clearly show anatomic location of the device and can quantify its effectiveness [8–10]. However MRI requires more patient compliance and a comprehensive MR exam takes time and is relatively expensive. Many stents, devices, and vascular filters are MR compatible. Whereas implantable cardiac devices have previously been considered as absolute contraindications, the FDA recently granted pre-market approval for an "MRI safe" pacemaker system (FDA press release February 8, 2011).

Other Noninvasive Imaging Modalities

Radionuclide techniques can also be used for the assessment of IC shunt. Radionuclide scintigraphy can be considered as an alternative noninvasive method for the quantification of IC shunt and evaluation of LV function in patients with post MI VSR [11].

Cardiac CT can provide comprehensive anatomic information in the assessment of congenital cardiac defects. Although cine CT makes some hemodynamic measurements possible such as cardiac output, quantification of IC shunts with CT has not been well established.

Invasive Quantification of Intracardiac Shunts

IC shunts have been calculated using various invasive methods. Indocyanin dilution and/or dye curve technique have been used in the past. Contrast angiography provides qualitative evaluation and localization of the shunts but is not suitable for precise shunt quantification. The widely used invasive technique is the oxymetric study, which is based on blood sampling from different locations in the circulation.

Oxygen Saturation Run

Knowledge of basic principles of Fick's method is fundamental to understand how IC shunts are calculated in catheterization laboratory.

Blood Sampling

Blood samples should be obtained after a "steady state" of heart rate, respiratory rate and blood pressure is reached. A large hole catheter should be used for easy blood draw. It should be kept in mind that very rapid aspiration or a faulty connection may allow entry of the micro bubbles into the syringe, resulting in erroneously increased O_2 saturation and overestimation of Q_p [12]. Sites for Blood sampling must be carefully chosen depending on the underlying pathology (Fig. 14.4) Blood sampling procedure should be completed within 5–10 min (or at the same time that oxygen consumption is calculated) in order to minimize the variability in oxygen consumption. After each sample is obtained, the catheter must be cleared with a saline flush. Obtaining blood samples from distal to proximal during catheter "pull-back" from pulmonary artery (PA) is more practical. If possible, the patient should not be receiving supplemental oxygen greater than 30% as the increased dissolved O_2 in the right heart might cause increased pulmonary flow resulting in overestimation of the shunt ratio.

Variability of oxygen measurements and oxygen content should be taken into account during the sampling process, particularly in the right-sided heart chambers. In a study with 980 patients [13] without shunting, differences of O_2 saturation were found between SVC and RA, RA and PA, SVC and PA $3.9 \pm 2.4\%$, $2.3 \pm 1.7\%$, and $4.0 \pm 2.5\%$, respectively. In another study, [14] 102 adults without left to right shunt were assessed in order to find the limits of normality of O_2 content differences. The outcomes were from right atrium to mixed venous, right ventricle to right atrium, and pulmonary artery to right ventricle, 0.5 mL/dL, 0.6 mL/dL, and 0.9 mL/dL, respectively.

Mixed Venous Oxygen Saturation

In the normal circulation, deoxygenated blood is mixed in the pulmonary artery (PA). However, in the setting of left to right shunt, site of mixed venous blood would vary according to the location of the lesion. Unfortunately, there is no practical way to measure mixed venous oxygen (MVO_2) because the various sources of MVO_2 (Superior vena cava, inferior vena cava, coronary sinus) have different amounts of blood with varying saturations. As a general rule, blood samples should be obtained proximal and distal to the lesion and blood from the chamber(s) proximal to the shunt site is used for MVO_2 measurement. For instance, in the case of patent ductus arteriosus (PDA), arterial blood mixes with venous blood at the pulmonary artery at the level of the aorta. Thus, venous samples should be taken from RV, which is the proximal chamber to the shunt site. In patients with a ventricular septal defect, RAO_2 saturation can represent MVO_2 site. In the case of an atrial septal defect, the location where the arterial shunt mixes with venous blood is not constant. Different formulae are used for the calculation of MVO_2. The most commonly used formula in the estimation of MVO_2 is $((3SVC + 1IVC)/4)$ [15]. Other formulae may also be considered for an estimation of MVO_2 as follows:

$$\mathrm{MVO_2} = \frac{((1 \times \mathrm{SVC_{Sat}}) + (2 \times \mathrm{IVC_{Sat}}))}{3} \quad \mathrm{MVO_2} = \frac{((2 \times \mathrm{SVC_{Sat}}) + (3 \times \mathrm{IVC_{Sat}}))}{5}$$

where $\mathrm{MVO_2}$ = Mixed venous oxygen saturation, $\mathrm{SVC_{Sat}}$ = Superior vena cava saturation, and $\mathrm{IVC_{Sat}}$ = Inferior vena cava saturation [14, 16].

Calculation of Shunt Size "Pulmonary to Systemic Flow Ratio (Q_p/Q_s)"

In the absence of a shunt, pulmonary blood flow (Q_p) is equal to the systemic blood flow(Q_s). Q_p/Q_s ratio is calculated based on Fick's principle as follows:

$$\text{Cardiac output} = \frac{\text{Oxygen consumption}}{(\text{Arterial } \mathrm{O_2} - \text{Venous } \mathrm{O_2}) \times \text{Hemoglobinconcentration} \times 1.36 \times 10}$$

Since the pulmonary circulation occurs between pulmonary veins and pulmonary artery, the formula is adapted as follows:

$$Q_p = \frac{\text{Oxygen consumption}}{(\mathrm{PVO_2} - \mathrm{PAO_2}) \times \text{Hemoglobin concentration} \times 1.36 \times 10}$$

where Q_p = Pulmonary blood flow, $\mathrm{PVO_2}$ = Pulmonary vein oxygen saturation, and $\mathrm{PAO_2}$ = Pulmonary artery oxygen saturation)

Systemic circulation takes place between the aorta and the point where the venous blood is assumed to be fully mixed. Therefore the formula corresponds to:

$$Q_s = \frac{\text{Oxygen consumption}}{(\mathrm{AoO_2} - \mathrm{MVO_2}) \times \text{Hemloglobinconcentration} \times 1.36 \times 10}$$

where Q_s = Systemic blood flow, $\mathrm{AoO_2}$ = Aortic or systemic arterial oxygen saturation, and $\mathrm{MVO_2}$ = Mixed venous oxygen saturation)

These formulae can be simplified to calculate Q_p/Q_s as follows:

$$\frac{Q_p}{Q_s} = \frac{(\mathrm{AoO_2} - \mathrm{MVO_2})}{(\mathrm{PVO_2} - \mathrm{PAO_2})}$$

For right to left or bidirectional shunts:

Effective pulmonary blood flow must be calculated. The net difference of systemic flow to shunt flow should be considered as effective pulmonary flow.

Clinical Utility of the Shunt Ratio in Practice

Shunt ratio (Q_p/Q_s) can help clinicians to better understand hemodynamic importance of the IC shunt and is clinically very important in decision making about the requirement of possible intervention. If the ratio is less than 1.5, it generally indicates a "small lesion," a ratio of 1.5–2.0 indicates "likely to require intervention," a ratio of 2 or more is usually considered to be "severe." Nevertheless, each case should be evaluated individually with its clinical presentation and shunt ratio should be determined within the clinical context of the disease state. If there is inconsistency between invasive and noninvasive measurements; symptoms attributable to shunt defect, possible associated congenital abnormalities, as well as measurement pitfalls should be carefully reviewed. Secondary findings such as quantification of chamber enlargement or ventricular function can also help in making decision.

Board Style Questions

Q1—A 30-year old woman presented with dyspnea on exertion. Echocardiographic examination revealed enlargement of right-sided heart chambers with an increased pulmonary flow. Left to right shunt was detected by color flow Doppler assessment in the inter-atrial septum. Which one of the following echocardiographic measurements is *not* necessary for the quantification of atrial shunt in this patient?

A) Diameter of LVOT
B) Diameter of RVOT
C) Diameter of defect
D) RVOT VTI
E) LVOT VTI

Q2—In which of the following congenital heart diseases, volumetric MRI measurement is *not* an appropriate method for the quantification of the intracardiac shunt?

A) Muscular type VSD
B) Secundum type ASD
C) Patent ductus arterious
D) Partial anomalous pulmonary venous return
E) Aorticopulmonary window

Q3—Which one of the following formulae can be used to estimate mixed venous blood (MVO_2) saturation during cardiac catheterization?

A)

$$MVO_2 = \frac{(3\times SVC_{sat} + 1\times IVC_{sat})}{4}$$

B)

$$MVO_2 = \frac{(SVC_{sat} + IVC_{sat})}{2}$$

C)

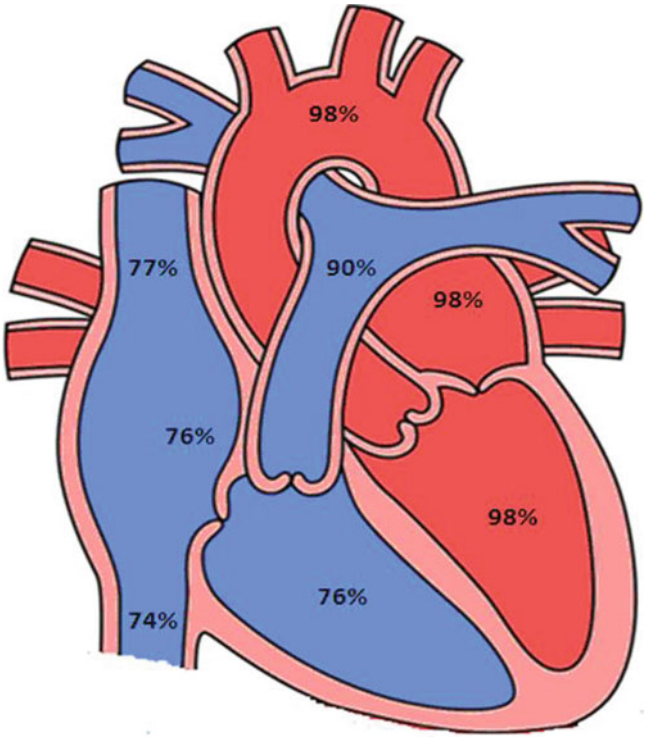
$$MVO_2 = \frac{(2 \times SVC_{sat} + 3 \times IVC_{sat})}{5}$$

D)

$$MVO_2 = SVC_{sat}$$

E) All of above

Q4—A 16-year old patient underwent cardiac catheterization for further investigation with the suspicion of congenital heart disease. Her hemoglobin level is 13 g/dL and calculated O_2 consumption is 190 mL/min. According to the saturation run study results, shown below, which is the correct diagnosis?



A) Muscular type VSD–$Q_p/Q_s = 1.5$
B) Ostium primum type ASD–$Q_p/Q_s = 2.8$
C) Ostium secundum type ASD–$Q_p/Q_s = 2.8$
D) Patent ductus arteriosus–$Q_p/Q_s = 2.8$
E) Patent ductus arteriosus–$Q_p/Q_s = 1.5$

Q5—A 36-year old man who was diagnosed secundum type ASD with left to right shunting. Calculated Q_p/Q_s ratio was reported as 2.1 with right atrial and ventricular enlargement. There was no associated significant valvular abnormality and he was still on normal sinus rhythm (68 beats/s).He was complaining of palpitations and exertional dyspnea and referred to you for further investigation and treatment. The following oxygen saturations were measured in catheterization room while patient was breathing 21% oxygen room air O_2 cont; IVCsat: 69%, SVCsat: 73%, PAsat: 80% Femoral artery sat: 98%.

What would you do for the next step in the evaluation of this patient?

A) Invasive Q_p/Q_s ratio cannot be calculated with these data; hemoglobin and cardiac output should have been reported.
B) Echocardiographic shunt ratio indicates significant left to right shunting with an enlargement of right-sided heart chamber, which is enough for the decision on closure of this ASD.
C) Room oxygen level is not enough; oxymetric study should be repeated while patient is breathing 80% oxygen.
D) Invasive Q_p/Q_s indicates significant left to right shunt so the defect should be closed as soon as possible.
E) Invasive Q_p/Q_s indicates nonsignificant left to right shunt, therefore patient should be treated medically and must be closely monitored.

Answers of the Questions

A1—The correct answer is C.
Echocardiography is the primary tool for the assessment of congenital heart disease. Although echocardiography can provide sizing of the defect, it is not required in the quantification of shunt ratio. The defect size, however, cannot give an idea about the shunt ratio. Small lesion can be associated with small shunt ratio whereas big lesions can be complicated by Eisenmenger physiology with right to left or bidirectional shunting.
A2—The correct answer is A.

Gradient echo cine MR can provide comprehensive volumetric assessment for both ventricles. The shunt volume can be easily calculated as net difference between LV and RV stroke volumes. In the setting of VSD, however, IC shunt occurs at the ventricular level and quantification of Q_p/Q_s is impossible using this method. On the other hand, if there is severe valvular regurgitation, due to substantial back flow into the atria, stroke volumes can be underestimated.

A3—The correct answer is E.

Although the most common formula is (3×SVC+IVC)/4, in the estimation of saturation MVO_2 blood**,** other formula can be considered.

A4—The correct answer is D.

The diagnosis is PDA with L□R shunt. O_2 step up can be clearly seen in main pulmonary artery. Although we can easily calculate Q_p/Q_s using simplified formula which is;

$$\frac{Q_p}{Q_s} = \frac{(AoO_2 - MVO_2)}{(PVO_2 - PAO_2)}$$

$$\frac{Q_p}{Q_s} = \frac{(98-76)}{(98-90)} = \frac{(22)}{(8)} = 2.75$$

Step by step approach for the assessment of intracardiac shunt quantification?

Step 1: Compute oxygen content for main locations

$$\text{Arterial oxygen content} = 0.98 \times 1.36 \times 13 \times 10 = 173$$

$$\text{Pulmonary vein oxygen content} = 0.98 \times 1.36 \times 13 \times 10 = 173$$

$$\text{Pulmonary artery oxygen content} = 0.90 \times 1.36 \times 13 \times 10 = 160$$

$$\text{Mixed venous oxygen content} = 0.76 \times 1.36 \times 13 \times 10 = 134$$

(Due to this is a PDA case, RVsat can represent MVO_2)

Step 2: Compute systemic flow (Q_s)

$$\frac{190}{173-134} = 4.87$$

Step 3: Compute pulmonary flow (Q_p)

$$\frac{190}{173-160} = 14.6$$

Step 4: Compute Q_p/Q_s

$$\frac{14.6}{4.87} = 3$$

A5—The correct answer is B.

Invasive oxymetric measurement of the Q_p/Q_s ratio is 1.5 which is inconsistent with echocardiographic shunt ratio. This is not uncommon situation in daily practice. Although Q_p/Q_s ratio is clinically very important in decision-making, if there is strong clinical suspicion or laboratory evidence of a significant shunt (this patient is symptomatic and TTE revealed right sided heart chambers enlargement), then defect should be closed. On the other hand, it should be kept in mind that atrial shunts can easily be affected by ventricular filling patterns such as compliance or stiffness and might be underestimated in the setting of severe tricuspid regurgitation or atrial fibrillation.

Hemoglobin and oxygen content are not exactly necessary for an estimation of Q_p/Q_s ratio. Because same parameters are used in the denominator and nominator of the equations, simplified method can be used practically.

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