12

Cardiac output monitoring

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Indications for cardiac output measurement

Evaluation of the cardiovascular status of critically ill patients is broadly divided into those parameters that relate to venous return to the heart and those that relate to forward flow from the heart. Parameters that evaluate venous return (preload; end-diastolic ventricular filling) include ease of jugular vein distention and central venous pressure, postcava diameter (radiography), and end-diastolic ventricular diameter (ultrasonography). Parameters that evaluate forward flow can be broadly divided as follows: (1) those that relate to cardiac output, such as heart rate, stroke volume, pulse quality, and cardiac output; (2) arterial blood pressure; (3) those that relate to arteriolar vasomotor tone, such as mucous membrane color and capillary refill time; and (4) those that relate to tissue perfusion, such as appendage temperature, urine output, gastric carbon dioxide tension, oxygen extraction ratio, venous oxygen tension, and metabolic acid–base balance (including blood lactate concentration).

There are various levels of knowledge involved in the evaluation of the cardiovascular status. Clinicians typically start with the collection of historical data and the physical examination of mental status, hydration status, ease of jugular vein distention, heart rate, pulse quality, mucous membrane color, capillary refill time (CRT), and appendage temperature. In many cases, based on the findings of this examination, a strong case can be made for hypovolemia, low cardiac output, or poor tissue perfusion and a therapy plan can be formulated. If the patient responds to therapy, no additional cardiovascular information is necessary. In other cases, the information derived from the initial history and physical examination is insufficient to comfortably define patient status, or the patient's response to the initial therapy is insufficient to restore clearly delineable normal-range cardiovascular values. Subsequent therapeutic decisions require additional information. A second level of cardiovascular information is gained by measuring parameters such as central venous pressure (CVP), postcava diameter, end-diastolic left ventricular diameter, arterial blood pressure (ABP), and parameters of metabolic acid–base balance; there are chapters in this textbook describing these techniques. Many times this additional information helps clarify the patient's cardiovascular status and facilitates subsequent therapeutic decisions. A few residual patients either still cannot be defined or do not respond to therapy; in such cases, additional information is required. It is at this point that flow information such as cardiac output and oxygen delivery might be helpful. Cardiac output can be measured many ways but the common clinically applicable techniques involve indicator dilution.

Indicator dilution techniques

Indicator dilution techniques basically involve the injection of a known volume of fluid (V_1) with a known concentration of indicator (C_1) into an unknown larger volume (V_2) and then measuring the concentration of the indicator in the larger volume of fluid (C_2). The unknown volume (V_2) is then calculated by the following formula:

$$C_1 \times V_1 = C_2 \times V_2 \qquad (12.1)$$

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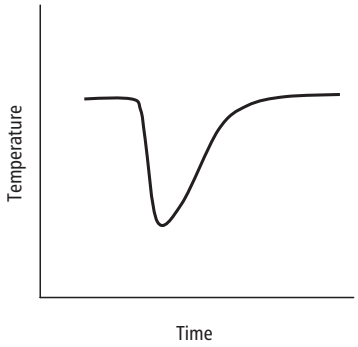

Figure 12.1 Temperature–time curve of a thermodilution cardiac output measurement. (Tracing can be displayed in either an upward or a downward direction.)

In a moving fluid such as the cardiovascular system, C_2 is calculated as the average change in indicator concentration over time.

Any indicator can be used as long as it can be measured with a rapidly responding sensor. In thermodilution, the indicator is temperature. A small volume of fluid (V_1) at a known temperature (T_1) is injected into the cranial vena cava or right atrium. This injected fluid flows and mixes with the blood through at least two heart valves. The change in temperature as the blood–fluid mix flows past a rapid-acting thermistor in the pulmonary artery or a peripheral artery is measured (see Fig. 12.1). The average change in temperature (T_2) is integrated from the change in temperature over time. The unknown volume of blood (V_2, the cardiac output) flowing along with the injected fluid is then calculated by the Stewart–Hamilton formula:

$$\text{Cardiac output} = V_1 \times (T_b - T_i) \times (\text{computation constant}) \div [\text{integrated area of the measured temperature change over time } (T_2)] \quad (12.2)$$

where V_1 is the volume of the injectate, T_b is baseline blood temperature, and T_i is the temperature of the injectate. The computation constant is calculated from the density and specific heat of the injectate compared with the density and specific heat of blood, and the change in temperature of the injected fluid as it traverses the catheter. The computation constant is provided by the equipment manufacturer. The computer calculates cardiac output in milliliters or liters per minute, and this value must then be indexed to body size either as kilograms of body weight or square meters of body surface area.

Thermodilution has been demonstrated to be accurate and repeatable in *in vitro* models[1–4] and when compared *in vivo* with dye dilution,[5] electromagnetic flowmetry,[6] and transit-time flowmetry.[7]

Transpulmonary thermodilution cardiac output measurements, with the thermistor placed in a peripheral artery (thus avoiding the use of the balloon-tipped thermodilution catheter), have been reported to accurately reflect traditional thermodilution cardiac output measurements made with the pulmonary artery catheter.[8–12] Using the transpulmonary thermodiluation method, extravascular lung water (pulmonary edema) can also be estimated.

Cardiac output can also be measured continuously with specialized thermodilution catheters that incorporate a thermal filament near the proximal port of the catheter that is positioned in the cranial vena cava or right atrium. The thermal filament cycles on and off. The change in temperature of the heated blood is sensed by the downstream thermistor in the pulmonary artery. Values for cardiac output, ejection fraction, end-diastolic volume, end-systolic volume, and stroke volume are generated as an average for the last 5–10 minutes. This methodology has been reported to compare well with intermittent thermodilution cardiac output measurements,[13–16] although low-range cardiac outputs may be overestimated while high-range cardiac outputs may be underestimated.[17]

Thermodilution cardiac output measurements are the standard of practice for clinical measurements of cardiac output in people. Balloon-tipped thermodilution catheters are, however, expensive, variably difficult to place, and are invasive. Measurements are subject to significant intermeasurement variation and therefore repeated measures, to obtain an average, are necessary and take time. Many studies compare the cardiac output estimates of a particular methodology with thermodilution; variance and bias are usually blamed on the compared methodology without regard to the inherent variability of thermodilution. This approach elevates thermodilution to "gold standard" status and unfairly biases against the tested methodology.

While thermodilution catheters permit the measurement or calculation of a large number of important cardiovascular parameters, their use has a variable record with regard to improved patient survival.[18–24] Although one might expect that increased monitoring should provide the means for improved patient care and, therefore, survival, there is no overwhelming evidence for this. The lack of demonstrable statistically significant survival benefit does not, however, prove that the thermodilution catheter is a useless monitoring tool. Thermodilution catheters were used ubiquitously in

human critical care and without regard for selecting patients who might truly be benefited. Of course, ultimate survival depends upon the effectiveness of the management of the underlying disease process, irrespective of the tools used to monitor the patient.

Lithium and indocyanine green (ICG) indicators are also used to measure cardiac output. The measurement is made by injecting a known amount of indicator into a central vein and withdrawing blood at a constant rate from an arterial catheter, past a lithium sensor or densitometer, respectively. Newer methods of ICG cardiac output use a transcutaneous finger photosensor[25] or ICG fluorescence[26] rather than an *ex vivo* cuvette densitometer. With the lithium indicator, cardiac output is calculated from the lithium dose and the area under the lithium concentration-versus-time curve:

$$\begin{aligned}\text{Cardiac output} = &[\text{lithium dose (mM)}] \times 60 \\ &\div [\text{integrated area under the} \\ &\text{concentration–time curve} \\ &\text{(mM/sec)} \times (1\text{-PCV})]\end{aligned} \quad (12.3)$$

where PCV stands for packed cell volume. Lithium dilution has been reported to compare well with thermodilution in dogs,[27] cats,[28] and foals.[29] One limitation to lithium and dye dilution techniques is the number of measurements that can be performed before background indicator concentrations start to interfere with subsequent measurements.

Balloon-tipped thermodilution catheter

Balloon-tipped catheters are available as two-lumen catheters for measuring pulmonary artery pressure and pulmonary artery occlusion pressure; as four-lumen catheters for measuring CVP, pulmonary artery pressure, and cardiac output (see Fig. 12.2); and as five- and six-lumen catheters for measuring CVP, pulmonary artery pressure, and cardiac output, for placement of pacing electrodes, and for continuous reflectance oximetry. Catheters are available in lengths of 80 (for pediatrics) or 110 (for adults) cm and in diameters of 4, 5, 6, 7, 7.5, or 8.5 Fr, depending upon the number of lumens and intended use. The cost of these catheters varies between about $80 for the simpler versions to $200 (in 2010) for the more comprehensive catheters. The 4-Fr catheter is the smallest diameter four-lumen catheter with thermodilution capabilities and can be used in cats and small dogs (1–3 kg). The 7-Fr four-lumen catheter can be used in dogs over 10 kg; 5- and 6-Fr catheters are suitable for dogs between 3 and 10 kg. Thermodilution cardiac output catheters are available from Arrow International (www.arrowintl.com) or Edwards Lifesciences (www.edwards.com). Cardiac output computers are available from many companies that market patient monitoring equipment (Baxter, Abbott, USCI, Siemens, Hewlett-Packard, Marquette, Space Labs, Spectramed, PPG, Elecath, Kontron, Lyons, Kone, Mennen, and Nihon Koden).

Insertion of the balloon-tipped thermodilution catheter and complications

Introduction of the catheter and repositioning of it after placement are facilitated by the use of an appropriate-sized introducer catheter, which incorporates a plastic cover sheath to protect the thermodilution catheter from contamination during the initial insertion as well as during subsequent repositioning.

The cardiac output computer and pressure monitor are turned on and readied. A bag of heparinized saline in a pressure bag is readied for the intrafusor. Introducer

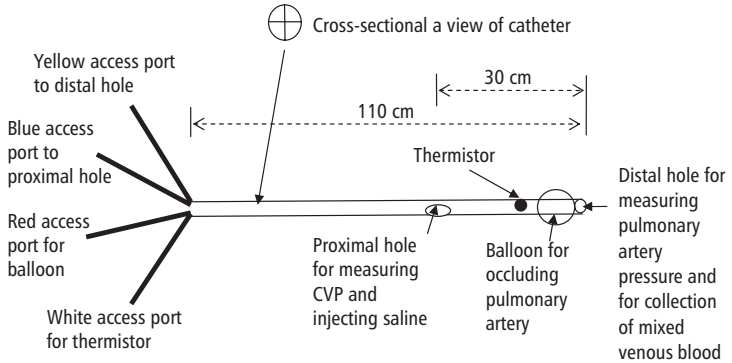

Figure 12.2 Schematic of a four-lumen, thermodilution, balloon-tipped catheter.

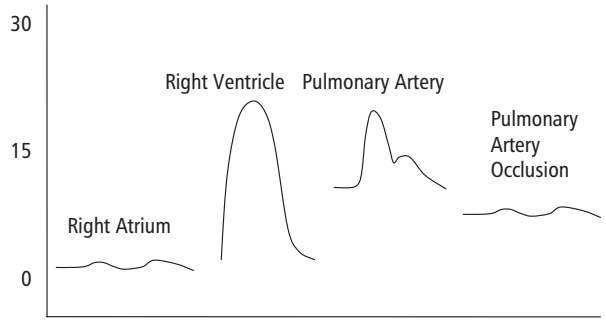

Figure 12.3 Schematic of representative pressure waveforms while introducing the balloon-tipped catheter into the pulmonary artery.

catheter kits and thermodilution catheter kits are opened. Catheters can be placed via the jugular vein or the saphenous or femoral vein. Introducer wires, introducer catheters, and thermodilution catheters are long and floppy, and are easily contaminated. Aseptic introduction must be assured. An area of at least 5-cm (2-inch) radius around the intended venipuncture site is clipped and aseptically prepared. Large sterile drapes are used to extend the sterile field.

First insert the introducer catheter and suture it in place. Next, the proximal port line of the thermodilution catheter is filled with sterile, heparinized saline and capped. The distal port line is flushed with heparinized saline and attached to a pressure transducer and a physiologic monitor for pressure measurements that will be used to identify the location of the catheter during its introduction. As the catheter is advanced toward the right atrium, a typical CVP tracing should be displayed on the monitor (see Fig. 12.3). Initially, angle the natural curvature of the catheter toward the sternum and the right ventricle. Marks on the catheter at 10-centimeter intervals identify how much of the catheter has been inserted. Typically the tip of the catheter will reach the right ventricle when it has been inserted to 25–40 cm, depending on the size of the patient. When the catheter enters the right ventricle the tracing will change to a typical ventricular pressure waveform (see Fig. 12.3). If the catheter has been introduced as far as 50 cm and has not entered the right ventricle, it has either coiled in the right atrium or passed into the caudal vena cava. The catheter should be withdrawn to 20 cm and reinserted. There is little directional control over the tip of the catheter and so, on subsequent reintroductions, the catheter should be rotated in one direction or another and readvanced until it ultimately ("accidentally") falls into the right ventricle. If the catheter end-hole butts up against a vessel or chamber wall, there will be a sudden cessation of pressure waveform on the monitor. If the line is attached to a high-pressure, low-volume, constant-infusion device (to prevent clotting within the catheter between measurements), the pressure tracing will increase rapidly to the top of the screen. Withdraw the catheter slightly, rotate it, and advance it again.

If the catheter fails to enter the right ventricle after repeated rotating (first one way then the other) and readvancing, try advancing the catheter with the balloon inflated; try shifting the position of the animal, insofar as possible. If all else fails and patience is at an end, use fluoroscopy to guide the introduction of the catheter.

Once the tip of the catheter is in the right ventricle, the balloon is inflated (1 mL) and further advanced until it enters the pulmonary artery (see Fig. 12.3). Once in the pulmonary artery, with the balloon still inflated, the catheter is further advanced until it occludes a branch of the pulmonary artery, at which time the pressure tracing will change to a typical occlusion pressure (see Fig. 12.3). Deflation of the balloon allows the measurement of pulmonary artery pressure; reinflation of the balloon allows the measurement of pulmonary artery occlusion pressure. During subsequent inflations of the balloon, always monitor the pressure tracing. When the catheter is first introduced, there is usually a big loop of catheter in the right ventricle. Over time, between measurements, the catheter will migrate further into smaller branches of the pulmonary artery. Full inflation of the balloon at this time could rupture these smaller pulmonary vessels. If less than full balloon inflation occludes the vessels (as indicated by the appearance of a typical occlusion pressure waveform on the monitor), the balloon should be deflated and the catheter should be withdrawn a short distance until it requires the full 1-mL inflation to occlude the vessel. The balloon should be inflated only for the measurement of occlusion pressure and then should be deflated; it should not remain inflated for an extended duration because continuous inflation will cause vessel damage. Step-by-step instructions for pulmonary arterial catheterization are available in Protocol 12.1.

Once the catheter is ideally positioned so that all measurements (central venous, pulmonary artery, and occlusion pressure) can be obtained, it should be secured to the patient and bandaged aseptically and occlusively.

Sepsis is a major hazard of these catheters. They are long and floppy and are easily contaminated during placement if one is not careful. Once placed, they are "busy" catheters in that they are frequently used throughout the day to make measurements and procure blood

Protocol 12.1 Insertion of the balloon-tipped thermodilution catheter

Items Required

- Appropriate-sized thermodilution catheter set
- Appropriate-sized introducer set with catheter guard sheath
- Pressure transducer
- Noncompliant fluid tubing, if desired
- Patient monitor with integrated cardiac output computer and associated power cord, thermistor cable, and transducer cable
- Hair clippers and surgical scrub solutions
- Surgical cap, mask, and sterile gloves
- Sterile surgical drapes
- Basic surgical set and skin-suitable suture such as 3–0 to 2–0 nylon
- Sterile syringes with needles
- Three-way stopcocks
- Heparinized saline
- Bag of 0.9% NaCl heparinized to 1 U/mL
- Standard fluid administration set
- Pressure bag
- At least one assistant

Procedure

1. Collect necessary supplies.
2. Turn on the cardiac output computer and patient monitor. Input any necessary information into the computer (volume and temperature of injectate).
3. Spike the heparinized saline bag with the standard fluid administration set and insert into a pressure bag. Make sure the administration set is clamped and capped.
4. Attach electrocardiograph(ECG).
5. Clip and prepare with antiseptic solutions a wide area of skin over the intended vessel puncture site.
6. Perform a surgical aseptic hand scrub. Don cap, mask, sterile gown, and sterile gloves.
7. Drape off introduction site to create a large sterile field.
8. Open introducer and catheter sets. Fill proximal port line with heparinized saline; clamp and cap this line.
9. Attach distal catheter port to pressure transducer via a three-way stopcock and flush the system with heparinized saline. If any fluid line is inserted between the patient and the transducer, it must be noncompliant tubing.
10. Attach continuous flush line to the transducer and pressurize the bag to ≥200 mm Hg.
11. Zero the pressure transducer. Zeroing information can be found in Protocol 8.2.
12. Insert the introducer catheter per manufacturer's recommendations and suture in place.
13. Insert the thermodilution catheter through the introducer catheter to about 20 cm and verify that the pressure tracing reflects a central venous pressure waveform.
14. Advance the catheter with the natural curve of the catheter aimed toward the sternum of the animal; watch for a typical ventricular waveform.
15. If the catheter advances to the 50-cm mark without entering the right ventricle, withdraw it to the 20-cm mark and start again.
16. It may help to twist the catheter, a little or a lot, in either direction, to change the chance that it might enter the right ventricle.
17. If the pressure tracing becomes damped, flush the distal port with the transducer's fast flush device; if the pressure tracing abruptly ceases followed by a rapid, linear increase, the end-hole has butted up against a vessel or heart chamber wall and should be withdrawn slightly and then reinserted.
18. It may help to change the position of the animal.
19. Once the catheter tip has entered the right ventricle, inflate the balloon with 1 mL of air and advance it further until the pressure waveform indicates that the catheter tip has entered the pulmonary artery.
20. With the balloon inflated, advance the catheter until the pressure tracing reflects occlusion of a branch of the pulmonary artery; deflate the balloon and verify a good pulmonary artery tracing.
21. Bandage the catheter and introducer set aseptically and occlusively.

samples. Everything that is done with and around these catheters must be accomplished with the utmost care and asepsis. Thus, the operator should perform hand hygiene and don clean gloves each time the catheter, its ports, or its sheath is handled. See Chapter 54, Minimizing Nosocomial Infection, for more information.

Physical contact of these catheters against the endocardium, especially during introduction, is occasionally associated with arrhythmias. Simply stop or withdraw the catheter slightly and then recommence the procedure once the arrhythmia has abated. Persistent arrhythmia problems could be treated with an antiarrhythmic such as lidocaine.

Catheter-associated clot emboli may occur but there is not much one can do to prevent it. It is not typical to administer anticoagulants to patients with these catheters any more than it is for any other catheter. Heparin-coated catheters are now available that may decrease this problem. Air emboli may occur if air is inadvertently injected into the catheter or into the balloon port if the balloon has ruptured.

Pulmonary vessel trauma and rupture has been reported in people due to leaving the balloon inflated or by fully inflating the balloon after the catheter has migrated.[30] Additional rarely reported complications include pneumothorax, hemothorax, and knotting of the catheter (in the right ventricle) during removal.

Thermodilution cardiac output measurement

To measure pressure, a pressure transducer and physiologic monitor are required; to measure cardiac output, a compatible cardiac output computer is required; to measure venous blood oxygen saturation, a compatible oximeter is required; and to pace the heart, a suitable catheter-tipped pacemaker and control unit are required.

To make a cardiac output measurement, the thermistor connection is attached to the cardiac output computer. Some systems incorporate an injectate-measuring thermistor at the injection port. The computer will calculate a compensated value for the change in temperature of the injectate as it traverses the catheter. Otherwise the temperature of the injectate (room temperature or iced) will need to be measured and entered into the computer. Usually room-temperature fluid is used. Ice water temperature fluid may be necessary for signal detection when smaller volumes of fluid are used in larger patients. Injectate volume must be entered into the computer. Usually a small volume of fluid (3–5 to 10 mL; smaller volumes for smaller patients) of a crystalloid fluid such as saline is used. After recording all of the measured pressures, the operator must indicate to the computer that an injection is about to be made; the computer will indicate when it is ready for injection to begin. The designated volume of fluid is injected into the cranial vena cava or right atrium. The operator should try to make the injection at the end of exhalation and as fast as possible. The computer will measure the change in temperature as the fluid–blood mixture passes by the thermistor in the pulmonary artery and will then calculate the average change in temperature and cardiac output. Typically make three to five measurements, discard outliers, and average the rest to obtain a representative cardiac output value. Please see Protocol 12.2 for step-by-step instructions for performing pressure and cardiac output measurements.

Lithium cardiac output measurement

A central venous and an arterial catheter are placed. The lithium sensor is attached via a three-way stopcock to the arterial catheter and to the cardiac output computer. Arterial blood will be withdrawn past this sensor at a constant rate of 4 mL/min and into a collection container. Hemoglobin and sodium concentration are premeasured and entered into the computer. A sensor constant and the intended lithium dose are also entered into the computer. The dose of lithium is 0.005–0.008 mM/kg and is generally injected as a 0.015–0.15 mM/mL solution; a change in blood lithium concentration of 0.2–0.8 mM/L is recommended to obtain a good signal for cardiac output calculation. The calculated dose of lithium is placed into an extension set attached to the jugular catheter. The pump for withdrawal of arterial blood and the cardiac output computer are started. The dose of lithium is flushed into the anterior vena cava after 5–10 seconds (the computer needs a little time to establish a baseline; larger animals may require the longer delays). The sensor measures the change in lithium concentration over time and the computer calculates cardiac output. The measurement should be repeated at least once, outliers excluded, and the remaining values averaged. Please see Protocol 12.3 for detailed instructions.

Other measurements and calculations

The units of the raw cardiac output measurements are milliliters (or liters) per minute and must be indexed to the size of the patient. The size of the patient can be expressed as either kilograms of body weight or square meters (m^2) of surface area (see Table 12.1).

The measurements that can be obtained from the thermodilution catheter are central venous pressure, pulmonary artery pressure, pulmonary artery occlusion pressure, and cardiac output. In addition, mixed venous

Protocol 12.2 Thermodilution cardiac output measurement

Items Required
- Patient with indwelling pulmonary arterial catheter
- Cardiac output computer-equipped patient monitor with associated thermistor and pressure-transducer cables; power cord
- Injectate with known temperature—room temperature (measured) or iced fluid (0°C [32°F])

Procedure: Pressure Measurements
1. Perform hand hygiene and don clean examination gloves.
2. Inflate balloon while observing pressure tracing. It should take the entire 1-mL balloon volume.
3. If an occluded pressure waveform appears with less than the full 1 mL, deflate the balloon and withdraw the catheter a couple centimeters, and try again.
4. If the full 1-mL balloon inflation fails to occlude the vessel, leave the balloon inflated and advance the catheter until the vessel occludes.
5. Deflate the balloon after the occlusion pressure measurement has been made. Record the occlusion pressure.
6. Record the central venous pressure and arterial blood pressure.

Procedure: Cardiac Output Measurement
1. Perform hand hygiene and don clean examination gloves.
2. Make sure that the cardiac output computer knows the volume and temperature of the injectate (temperature is either measured or it must be input by the operator). Enter the computation constant if necessary. Make sure that the thermistor cable is attached to the computer.
3. Push the button on the cardiac output computer to tell it that you want to make a measurement; the computer will tell you when it is ready for you to inject.
4. At the end of a breath, rapidly inject a volume of injectate into the proximal port (patient weight less than 3 kg, use 3 mL; 3–25 kg, 5 mL; >25 kg, 10 mL).
5. Record the measurement.
6. Repeat measurement 3–5 times; discard outliers; average the remaining values.
7. Index to body size.

Protocol 12.3 Lithium cardiac output measurement

Items Required
- A lithium sensor and cardiac output computer
- Preplaced jugular venous and arterial catheters
- Three-way stopcock
- A roller pump and scavenge bag to withdraw blood at 4 mL/min

Procedure
1. Collect necessary supplies.
2. Perform hand hygiene and don clean examination gloves.
3. Premeasure hemoglobin and sodium concentration and enter into computer. Input sensor constant and intended lithium dose (0.005–0.008 mM/kg).
4. Attach lithium sensor, extension set, roller pump, and scavenge bag to the arterial catheter via the side-port of a three-way stopcock.
5. Measure and record central venous and arterial blood pressure.
6. Charge the extension set on the jugular catheter with the dose of lithium (0.005–0.010 mM/kg).
7. Start the roller pump and blood withdrawal at 4 mL/min and push the button to tell the computer that you are ready to make a measurement.
8. After 5–10 seconds, depending on the size of the animal (<5 kg, 5 seconds; 5–30 kg, 6–7 seconds; >30 kg, 8–10 seconds), rapidly inject the lithium at the end of a breath.
9. Repeat the measurement at least once and average similar values.
10. Index to body size.

blood samples can be obtained from the distal port of this catheter for pH and blood gas analysis. If a separate arterial catheter is placed, arterial blood pressure and arterial blood samples (for pH and blood gas analysis) can be obtained. In addition to cardiac output, measurements that can be obtained during lithium cardiac output measurements include central venous pressure and blood sampling, and arterial blood pressure and blood sampling (for pH and blood gas analysis).

Once cardiac output is measured, heart rate is measured separately and stroke volume can be calculated. When arterial and pulmonary pressure and cardiac output are measured, systemic arterial and pulmonary vascular resistance and left and right heart work indices can be calculated. When hemoglobin concentration and PO_2 are known, oxygen content can be calculated. When cardiac output and oxygen content are known, oxygen delivery can be calculated. When cardiac output and arterial and mixed-venous oxygen content are known, the oxygen consumption and extraction and the venous admixture can be calculated. Table 12.2 contains standard calculations.

Table 12.1 Body Weight to Surface Area Conversion Table*

Weight		Surface Area	Weight		Surface Area
Kilograms	Pounds	(sq meter)	Kilograms	Pounds	(sq meter)
0.5	1.1	0.06	26	57.2	0.89
1	2.2	0.10	27	59.4	0.91
2	4.4	0.16	28	61.6	0.93
3	6.6	0.21	29	63.8	0.95
4	8.8	0.25	30	66	0.98
5	11	0.29	31	68.2	1.00
6	13.2	0.33	32	70.4	1.02
7	15.4	0.37	33	72.6	1.04
8	17.6	0.40	34	74.8	1.06
9	19.8	0.44	35	77	1.08
10	22	0.47	36	79.2	1.10
11	24.2	0.50	37	81.4	1.12
12	26.4	0.53	38	83.6	1.14
13	28.6	0.56	39	85.8	1.16
14	30.8	0.59	40	88	1.18
15	33	0.61	41	90.2	1.20
16	35.2	0.64	42	92.4	1.22
17	37.4	0.67	43	94.6	1.24
18	39.6	0.69	44	96.8	1.26
19	41.8	0.72	45	99	1.28
20	44	0.74	46	101.2	1.30
21	46.2	0.77	47	103.4	1.32
22	48.4	0.79	48	105.6	1.34
23	50.6	0.82	49	107.8	1.36
24	52.8	0.84	50	110	1.38
25	55	0.86			

Source: Hand MS, Thatcher CD, Remillard RL, et al., Body surface area of dogs. In: *Small Animal Clinical Nutrition*. 4th ed. Topeka: Mark Morris Institute; 2000:1009.
*$(10.1 \times kg^{0.67})/100$.

Other methods of estimating cardiac output

Thermodilution cardiac output measurement is the standard against which other methodologies are often compared in the clinical measurement of cardiac output. Electromagnetic flowmetry is the gold standard for experimental blood flow measurement. Flow probes can be surgically placed around a suitably size-matched vessel of interest or flow catheters can be introduced into a large vessel. The application of a magnetic field perpendicular to the blood flow induces an electrical potential proportional to the blood flow velocity that can be easily and accurately calculated. Flow is calculated from flow velocity and conduit diameter. Other methods of measuring cardiac output have been recently reviewed.[31,32]

The Fick Method

The *Fick* principle assumes that flow is proportional to the rate of uptake of an indicator gas, and the difference between the concentration of the indicator gas entering and exiting the organ being studied:

$$\text{Flow} = (\text{indicator gas uptake}) \div [(\text{gas conc. in}) - (\text{gas conc. out})] \quad (12.4)$$

Various marker gases have been used: oxygen, carbon dioxide, acetylene, and nitrous oxide. If any two parameters in this equation are known, the third can be calculated. When cardiac output is measured, for instance, arterial and venous oxygen content are calculated (from PO_2 and hemoglobin measurements; see Table 12.2), and oxygen consumption (VO_2) is calculated (flow times arterial–venous O_2 content). The venous blood sample used for these calculations must come from a central vein (pulmonary artery best; vena cava acceptable); cephalic or saphenous venous blood oxygen measurements will not do for this calculation. By the Fick equation, cardiac output can be calculated from oxygen consumption (calculated as the difference between inspired tidal volume and oxygen concentration and expired tidal volume and oxygen concentration) divided by arterial–venous O_2 content. Fick cardiac output estimates compared well with thermodilution cardiac output measurements in cats at low ($r = 0.89$) and normal ($r = 0.69$) cardiac outputs, but overestimated high ($r = 0.75$) cardiac outputs.[33] Fick cardiac output estimates compared well with dye-dilution cardiac output measurements in anesthetized dogs[34] and pigs.[13]

Arterial–venous oxygen content, oxygen extraction, venous oxygen, arterial–venous oxygen saturation

Oxygen consumption is usually not measured in clinical veterinary medicine so the whole Fick equation (Eq. 12.4) usually cannot be used. However, assuming that oxygen consumption has not changed too much (although it can easily halve [hypothermia; general anesthesia] or double [increased muscular activity] in common clinical situations), the arterial–venous oxygen content difference alone can be used to estimate the adequacy of tissue perfusion (directly related to cardiac output *if the animal is not vasoconstricted*). When oxygen delivery decreases, and oxygen uptake continues at its previous level, a greater proportion of oxygen is removed from the blood (oxygen extraction). This will

Table 12.2 Standard Formulas for Calculated Variables

Parameter	Formula
Body surface area	$(10.1 \times kg^{0.67})/100$
Alveolar PO_2 (room air)	[(barometric pressure-50) × 0.21]-($PaCO_2$/RQ), where 50 is the saturated water vapor pressure at 38.5°C, 0.21 is the fractional inspired oxygen, and RQ = 0.9
Arterial, mixed venous, and capillary oxyhemoglobin saturation	$([38{,}848/(202 \times PO_2 + 1.17 \times PO_2^2 + PO_2^3)] + 1)^{-1} \times 100$*
Arterial, mixed-venous, and pulmonary capillary oxygen content	$(1.34 \times Hb \times SO_2) + (0.003 \times PO_2)$, where 1.34 is 100% saturated hemoglobin oxygen content, SO_2 is hemoglobin saturation, PO_2 is partial pressure of oxygen in arterial, mixed venous, or capillary blood
Cardiac index	Cardiac output per square meter BSA or kilogram of body weight
Stroke volume index	CI/heart rate
Systemic vascular resistance index	(ABP-CVP) × 79.92/CI m^2 or (ABP-CVP)/CI kg
Pulmonary vascular resistance index	(PAP-PAOP) × 79.92/CI m^2 or (PAP-PAOP)/CI kg
Left and right cardiac work index	CI × ABPm × 0.0144 CI × PAPm × 0.0144
Left and right ventricular stroke work	SVI × ABPm × 0.0144 SVI × PAPm × 0.0144
Oxygen delivery	$CaO_2 \times$ (CI $m^2 \times 10$) or (CI kg/100)
Oxygen consumption	(CaO_2-$CmvO_2$) × (CI $m^2 \times 10$) or (CI kg/100)
Oxygen extraction	VO_2/DO_2 or (CaO_2-$CmvO_2$)/CaO_2
Venous admixture	(CcO_2-CaO_2)/(CcO_2-$CmvO_2$)
Arterial and venous blood carbon dioxide content	$(2.226 \times 0.0299 \times PCO_2 \times (1 + 10^{(pH-6.085)})) \times (1-((0.0289 \times Hb)/((3.352-(0.456 \times (SO_2/100))) \times (8.142-pH))))$**
Carbon dioxide production	($CaCO_2$-$CmvCO_2$) × CI × 10

*Reeves RB, et al., Oxygen affinity and Bohr coefficients of dog blood. *J Appl Physiol* 1982;53:87–95.
**Douglas AR, et al., Calculation of whole blood CO_2 content *J Appl Physiol* 1988;65:473–477.

result in a decrease in venous oxygen and a greater difference between arterial and venous oxygen content. Arterial–venous oxygen content was reported to be 3.6 ± 1.2 mL/dL in normal dogs, increasing to 7.0 ± 1.9 mL/dL in moderately hypovolemic dogs.[35] In this same report, oxygen extraction increased from 21 ± 6% to 42 ± 10%. Oxygen extraction is calculated by the following formula:

$$\text{Oxygen extraction} = (\text{Cont}_{\text{Art}}\ O_2 - \text{Cont}_{\text{Ven}}\ O_2)/\text{Cont}_{\text{Art}}\ O_2 \quad (12.5)$$

Central venous oxygen (partial pressure [PO_2] or saturation [SO_2]) alone (without calculating oxygen content) can also be used in this same context. Normal central venous PO_2 and SO_2 were reported to be 49 ± 6 and 78 ± 6, respectively, in normal dogs and decreased to 35 ± 5 and 56 ± 9 in moderate hypovolemia.[35] In another canine acute hemorrhage model,[36] PvO_2 decreased from 46 to 34 mm Hg. Venous PO_2 was reported to be significantly correlated with cardiac output in cats; however, there was notable variability.[33] In a cohort of critically ill humans, dobutamine augmentation of cardiac output, decreased oxygen extraction from 48% to 36% and increased mixed-venous oxygen saturation from 49% to 61%.[37] Other studies reported weak correlations between venous oxygen saturation and cardiac output in human intensive-care-unit patients[38] and in a piglet hemorrhagic shock model.[39]

Carbon dioxide–based Fick

The Fick principle and formula can also be used with carbon dioxide production:

$$\text{Flow} = (\text{carbon dioxide production})/(CvCO_2 - CaCO_2) \quad (12.6)$$

A commercial, noninvasive method for measuring cardiac output in intubated patients is available ($NICO_2$, Novametrix Medical Systems, Wallingford, CT). The method involves the transient partial rebreathing of carbon dioxide (for 50 seconds every 3 minutes). Cardiac output is calculated from end-tidal carbon dioxide concentrations during normal and CO_2 rebreathing episodes. End-tidal CO_2 (measured) and carbon dioxide solubility are used to calculate arterial CO_2 concentration. Inspired oxygen and arterial oxygenation are used to calculate a shunt fraction, which is used to correct for the shunted portion of cardiac output.[40,41] This method of analysis has been shown to compare favorably with normal-range thermodilution cardiac output measurements (but overestimated cardiac output at low-range cardiac outputs and underestimated high-range cardiac outputs).[17] The $NICO_2$ system compared well with ultrasound transit time flowmetry and thermodilution during and after cardiopulmonary bypass,[7] and with lithium cardiac output measurements, across a spectrum of low to high cardiac outputs, in anesthetized dogs.[41] The $NICO_2$ system is noninvasive, easy to use, and provides near-continuous measurements.

Venous–arterial PCO_2

Carbon dioxide production is not measured in clinical veterinary practice and so the whole Fick equation (Eq. 12.6) cannot be used. However, assuming that carbon dioxide production has not changed too much (although it can easily halve [hypothermia; general anesthesia] or double [increased muscular activity] in common clinical situations), the venous–arterial PCO_2 difference alone can be used to estimate the adequacy of tissue perfusion (directly related to cardiac output *if the animal is not vasoconstricted*). When blood flow decreases, and carbon dioxide production continues at its previous level, an increase in venous carbon dioxide results in a greater difference between arterial and venous PCO_2. Venous–arterial PCO_2 was reported to be 4.2 ± 1.5 in normal dogs, increasing to 10.7 ± 3.9 in moderately hypovolemic dogs.[35] In a canine acute hemorrhage model, venous–arterial PCO_2 increased from 5.2 to 12.9 mm Hg.[36] Venous–arterial PCO_2 was 4.9 in critically ill people with normal cardiac output measurements and was 7.4 in patients with low cardiac output.[42] Venous–arterial PCO_2 decreased from 9 to 5 mm Hg with dobutamine augmentation of cardiac output.[37]

Pulse contour methods

The area under the pulse pressure waveform bears some correlation to stroke volume. The pulse pressure waveform can be qualitatively characterized by digital palpation of an arterial vessel; a tall, wide pulse is likely associated with a large stroke volume while a short, narrow pulse is likely associated with a small stroke volume. The pulse pressure waveform can also be measured by indirect sphygmomanometry or by direct arterial measurement.

Pulse contour methodologies calculate stroke volume from measured pulse pressure waveforms using algorithms that consider arterial impedance, compliance, and resistance. At a given arterial compliance there is a directional relationship between the change in the

area under the pulse pressure waveform and the change in volume (stroke volume). Unfortunately, arterial compliance is not measured and so cardiac output must be periodically and independently verified. Once this measured cardiac output is fed into the computer, it back-calculates correction factors that will be used in future pulse-contour assessments (until it is again recalibrated). There are several commercial devices that continuously measure and assess the pulse pressure waveform.

The $PiCCO_2$ system (Pulsion Medical Systems, Irving, TX) requires a central venous and an arterial catheter. The $PiCCO_2$ system uses transpulmonary thermodilution to intermittently measure cardiac output (saline is injected into a jugular catheter and the change in temperature is measured by a thermistor in a special arterial catheter). The $PiCCO_2$ system also estimates cardiac filling volume, intrathoracic blood volume, and extravascular lung water. The $PiCCO_2$ system compared very well with thermodilution cardiac output measurements in critical human patients.[9,10,12,43–45] and in a piglet hemorrhagic shock model.[39]

The LiDCO Plus system (LiDCO Ltd Cambridge, UK) uses a pulse power analysis algorithm (PulseCO) that mathematically calculates changes in stroke volume; independent lithium indicator dilution cardiac output measurements are needed to calibrate the system. There is good agreement with thermodilution cardiac output measurements but large variability. Accuracy falls off with time and periodic recalibration (by remeasuring cardiac output) as often as every 1–2 hours may be necessary.[12] The PulseCO system has been reported to compare well with thermodilution and lithium cardiac output measurements (but overestimated cardiac output at low-range cardiac outputs and underestimated high-range cardiac outputs).[17,32,46,47] Early canine studies of pulse contour cardiac output estimates reported good correlation and accuracy compared with implanted electromagnetic flowmeter measurements[48,49] and thermodilution cardiac output measurements.[50] Several subsequent canine studies, however, have reported a high variability and poor correlation between pulse contour cardiac output estimates and lithium calibration cardiac output measurements.[51–53]

The MostCare™ device (Vytech Health, Padova, Italy) uses the pressure recording analytical method (PRAM), via perturbation theory, to estimate cardiac output just from the analysis of the pressure wave profile (requires only an arterial catheter). The PRAM algorithm characterizes the elastic properties of the arterial system from the analysis of the pulse pressure profile. The PRAM system also provides a parameter called cardiac cycle efficiency, which is an index of heart–vascular response coupling (+1 = best; −1 = worst). Cardiac cycle efficiency is a ratio between myocardial work and energy consumed, and represents an index of heart stress. PRAM compares very well with thermodilution cardiac output in people,[54] and with electromagnetic flowmetry and thermodilution cardiac output measurements in pigs across a wide range of cardiac outputs.[55]

The Portapres system (Finapress Medical Systems, Amsterdam, The Netherlands) is an ambulatory blood pressure monitoring unit that measures heart rate and blood pressure, calculates stroke volume and cardiac output, and calculates vascular resistance, compliance, and impedance. The technology compares well with thermodilution cardiac output in critically ill humans as a clinically acceptable trend monitor, but the substantial variation of measurements leads to a significant percentage of inaccurate measurements.[56,57]

The Flo Trac sensor and Vigileo monitor system (Edwards Lifesciences, Irvine, CA) utilizes user-entered anthropomorphic data (sex, age, weight, height, and surface area) to assign a value to compliance and vascular tone independent of external cardiac output measurements and system recalibration. For use in veterinary medicine, either the algorithms would need to be changed or false information would have to be entered to enable correct surface-area calculations. Flo Trac compared well with thermodilution cardiac output measurements.[32,45] The sensor can be used with any arterial catheter and no external calibration is required.

Transthoracic impedance

The transthoracic impedance method uses four paired electrodes to measure changes in transthoracic impedance during the cardiac cycle and then calculates an estimate of stroke volume. Over a cardiac cycle, the only intrathoracic fluid volume that changes is intrathoracic blood volume. The magnitude and rate of change reflects myocardial contractility. Baseline impedance is affected by other fluid accumulation diseases such as hydrothorax and pulmonary edema. A meta-analysis of thoracic impedance technology concluded that the technique may only be sufficiently accurate as a trend monitor.[58] There are several commercial devices that measure and assess the thoracic impedance.

The BioZ ICG system (Cardiodynamics, San Diego, CA, subsidiary of Sonosite, Bothel, WA) evaluates heart rate, blood pressure, cardiac output, systemic vascular resistance, systolic time ratio (an index of myocardial contractility), and thoracic fluid content. Studies generally report moderate correlation with thermodilution

cardiac output measurements[59,60] or between thoracic fluid content and the amount of fluid removed by hemodialysis.[61]

Electrical cardiometry (Icon and Aesculon [Cardiotronic, Inc. La Jolla, CA]) utilizes electrical velocimetry (changes in thoracic conductivity caused by the alignment of red blood cells) to calculate heart rate, stroke volume, cardiac output, systolic time ratio, an index of contractility, and thoracic fluid index. Electrical velocimetry estimates of cardiac output compared favorably with transpulmonary thermodilution cardiac output measurements in piglets.[11]

The RheoCardioMonitor (ACMA, Ltd, Singapore) assesses cardiac output and compared well to thermodilution cardiac output measurements in pigs[62] and people.[63]

The Niccomo instrument (Medis, Ilmenau, Germany) measures heart rate and blood pressure and utilizes a physiological adaptive signal analysis (PASA) algorithm to calculate stroke volume, cardiac output, systemic vascular resistance, thoracic fluid content, left cardiac work index, several indices of contractility, and systolic time intervals. The company also produces computer-based impedance cardiography interfaces, using the same technology as the Niccomo that can run on any personal computer (Cardioscreen 1000 and 2000). The PASA-algorithm-derived cardiac output correlated well with thermodilution in people[64]; other studies reported only modest correlation between impedance-estimated cardiac output and transthoracic Doppler cardiography[65] and thermodilution cardiac output.[56]

Whole-body impedance estimates of cardiac output correlated well with thermodilution cardiac output measurements in one study[66] but not in another.[67]

Doppler ultrasound

Standard echocardiography, operated by experienced individuals, can be used to measure aortic or pulmonary valve diameter and the velocity–time integral, from which stroke volume can be calculated. Accurate assessment of the diameter of the outflow tract is difficult, and measurements are intermittent and not a readily viable option for critical care settings. Echocardiographic estimated cardiac output did not correlate well with thermodilution cardiac output measurements in cats.[33] In a hemorrhage model in dogs, the pulmonic valve, compared with the aortic valve, and proximal and distal aorta, was the site that generated the most repeatable Doppler measurements,[36] but none of the echocardiographic cardiac output determinations compared very well with thermodilution.

The ultrasound cardiac output monitor (USCOM, Uscom Ltd, Sydney, Australia) uses continuous-wave Doppler and anthropomorphic aortic and pulmonary valve data to calculate stroke volume. There are no reports of its use in dogs and cats.

Doppler probes can also be placed into the esophagus and positioned so as to face the descending thoracic aorta (Hemosonic 100, Arrow International, Reading, PA; Dynemo 3000, Sometec, Paris). The ultrasound transducer is positioned as close as possible to the direction of blood flow (corrections are made to the measurement to compensate for the angle between the direction of the ultrasound beam and that of the blood flow). The phase shift in the reflected ultrasound waves as they are carried downstream by the flowing blood is used to calculate blood flow velocity. Flow velocity and time are used to calculate stroke distance, and stroke distance times cross-sectional area of the aorta (measured or anthropomorphically determined) is used to calculate stroke volume. A major assumption of this technique is that a constant proportion of the cardiac output flows through the descending aorta (the remainder going through the brachiocephalic and coronary arteries). Unfortunately this is variable; hypovolemia decreases and vasodilation increases the proportion of the cardiac output entering the descending aorta. Although some reports suggest good correlation with thermodilution cardiac output,[44,68–70] other reports suggest a variable correlation.[71] Use of the technique has been reported in anesthetized dogs, but cardiac output values were not reported.[72] Transesophageal probes are large, anesthesia is required to introduce them, and they cannot be fixed in place for continuous measurements.

Other methods

Velocity encoded phase contrast magnetic resonance imaging is a very accurate technique for measuring flow in large vessels.[73] Nuclear scintigraphy can also be used to evaluate cardiac output.[74] The equipment is very expensive, requires considerable training to operate, and the measurements are intermittent. These techniques do not lend themselves to use in the intensive care unit.

Interpreting measurements

There is a large amount of cardiopulmonary function information that can be derived when cardiac output is measured (see Fig. 12.4 and Table 12.3). This allows for broader characterization of patient status and may improve survival opportunities for some patients. Since forward flow is dependent upon venous return, it is

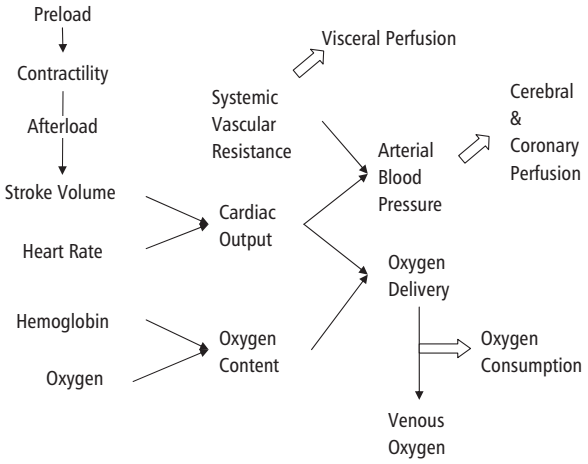

Figure 12.4 Integrated cardiopulmonary function: preload determines diastolic filling of the heart; contractility is the strength of load-independent contraction of the ventricles; afterload is the pressure against which the heart must contract to generate a stroke volume; stroke volume and heart rate determine cardiac output; hemoglobin concentration and the amount of oxygen loaded onto it determine oxygen content; cardiac output and systemic vascular resistance determine arterial blood pressure; arterial blood pressure is primarily important as a determinant of cerebral and coronary perfusion; systemic vascular resistance is primarily important as a determinant of visceral tissue perfusion; cardiac output and oxygen content determine oxygen delivery; oxygen delivery minus oxygen consumption determine venous oxygen.

appropriate to first evaluate preload parameters. Central venous pressure represents preload pressure to the right heart (0–10 mm Hg); pulmonary artery occlusion pressure represents preload pressure to the left heart (2–12 mm Hg). Low pressures suggest that there is room for additional blood volume augmentation if other parameters corroborate hypovolemia. High pressures may represent hypervolemia or heart failure, and suggest that additional volume loading may be unwarranted. Preload pressure has a variable relationship to preload volume, depending upon ventricular compliance. High preload pressure does not necessarily define high preload but it always necessitates a conservative fluid plan.

Next evaluate arterial blood pressure. Low mean arterial blood pressure (<60 mm Hg) could be caused by hypovolemia (check preload parameters), poor cardiac output (measure cardiac output; check for cardiac disease), or vasodilation (calculate systemic vascular resistance; check clinical vasomotor tone signs). High mean systemic arterial pressure (>140 mm Hg) is usually attributable to high vasomotor tone (iatrogenic hypervolemia is possible; high cardiac output and arteriosclerosis are unlikely).

Next evaluate cardiac output. Low cardiac output could be caused by the following: hypovolemia (check the preload parameters); cardiac disease (atrioventricular [AV] insufficiency, aortic stenosis, fibrosis, pericardial tamponade); poor contractility (if not measured, then presumed if preload parameters are high and forward flow parameters are low, in the absence of anatomic cardiac disease). Low cardiac output should be treated if it is associated with hypotension or evidence of poor tissue perfusion.

Next evaluate systemic vascular resistance. Low vascular resistance (vasodilation) may be associated with hypotension, in which case, it should be treated by administering a vasoconstrictor. Low vascular resistance associated with acceptable blood pressure does not need to be treated. High vascular resistance (vasoconstriction) may be associated with poor tissue perfusion. If associated with high blood pressure, the situation may benefit from judicious vasodilator therapy. However, if associated with marginal blood pressure, the condition should not be specifically treated because it is probably compensation for hypovolemia or marginal cardiac output, and vasodilator administration will probably cause hypotension.

Next evaluate oxygen content, delivery, consumption, and extraction. Low oxygen content is most likely caused by anemia. Low oxygen delivery may be caused by low oxygen content or low cardiac output. Low oxygen consumption may be caused by low oxygen delivery or impaired metabolism. High oxygen extraction is usually indicative of low oxygen delivery; low oxygen extraction may be caused by impaired cellular metabolism or peripheral arterial–venous shunting. Venous oxygen is low when oxygen extraction is high, and vice-versa; the assessments are the same.

Conclusion

Determination of cardiac output and systemic oxygen delivery can be helpful in patients with perfusion status that is poorly defined by other methods or that do not respond to therapy. Cardiac output can be measured many ways but the common clinically applicable techniques involve indicator dilution, usually either thermodilution with the balloon-tipped pulmonary arterial catheter or lithium dilution. Though it is unclear whether use of this advanced monitoring improves outcome, certainly outcome can only be improved if the technique is performed properly, the results interpreted correctly, and the appropriate therapy instituted.

Table 12.3 Cardiopulmonary Values in Normal Dogs[75]

Parameter	Units	Baseline	95%
		$n = 97$	Confidence
		Mean ± SD	Interval
BW	kg	20.5 ± 6.9	
BSA	m^2	0.74 ± 0.17	
Temp	°C	38.4 ± 0.6	38.3–38.5
pHa	Units	7.381 ± 0.025	7.376–7.387
$PaCO_2$	mm Hg	40.2 ± 3.4	39.5–41.0
HCO_3a	mEq/L	23.1 ± 2.0	22.7–23.5
BDa	mEq/L	–2.1 ± 2.3	–1.7 to –2.6
pHmv	Units	7.362 ± 0.027	7.356–7.367
$PmvCO_2$	mm Hg	44.1 ± 3.8	43.3–44.9
HCO_3mv	mEq/L	24.2 ± 2.1	23.7–24.6
BDmv	mEq/L	–1.9 ± 2.3	–1.4 to –2.3
a–mv pH	Units	0.020 ± 0.012	0.018–0.022
a–mv PCO_2	mm Hg	–3.9 ± 1.6	–3.6 to –4.2
a–mv HCO_3	mEq/L	–1.1 ± 0.7	–0.9 to –1.2
a–mv BD	mEq/L	0.2 ± 0.7	0.1–0.4
PaO_2	mm Hg	99.5 ± 6.8	98.1–100.8
SaO_2	%	96.3 ± 0.9	96.1–96.5
Hb	g/dL	13.6 ± 1.8	13.3–14.0
CaO_2	mL/dL	17.8 ± 2.3	17.4–18.3
$PmvO_2$	mm Hg	49.3 ± 5.8	48.2–50.5
$SmvO_2$	%	77.1 ± 5.5	75.6–78.2
$CmvO_2$	mL/dL	14.2 ± 2.2	13.8–14.7
$Ca–vO_2$	mL/dL	3.6 ± 1.0	3.4–3.8
PAO_2	mm Hg	105.8 ± 3.7	105.1–106.9
$A–aPO_2$	mm Hg	5.5 ± 6.9	3.6–7.4
ScO_2	%	96.9 ± 0.5	96.8–97.0
CcO_2	mL/dL	18.0 ± 2.3	17.5–18.5
Ven admix	%	3.6 ± 4.1	2.8–4.4
$CaCO_2$	mL/dL	45.8 ± 4.3	44.9–46.6
$CmvCO_2$	mL/dL	48.5 ± 4.4	47.6–49.4
$Ca–vCO_2$	mL/dL	2.7 ± 1.4	2.5–3.0
CVP	cm H_2O	3.1 ± 4.1	2.3–4.0
PAOP	mm Hg	5.5 ± 2.9	4.8–6.2
HR	Beats/min	87 ± 22	83.0–91.8

Table 12.3 (*Continued*)

Parameter	Units	Baseline	95%
		n = 97	Confidence
		Mean ± SD	Interval
ABPm	mm Hg	103 ± 15	99.9–106.0
PAPm	mm Hg	14.0 ± 3.2	13.4–14.7
CO	mL/min	3360 ± 1356	3086–3633
CI	L/min/m^2	4.42 ± 1.24	4.17–4.67
	mL/min/kg	165 ± 43	156–174
SVI	mL/beat/m^2	51.9 ± 13.5	49.2–54.7
	mL/beat/kg	1.93 ± 0.46	1.84–2.02
SVRI	dyne·sec·cm^{-5}/m^2	1931 ± 572	1815–2045
	mm Hg/mL/min/kg	0.641 ± 0.173	0.606–0.676
PVRI	dyne·sec·cm^{-5}/m^2	196 ± 78	179–210
	mm Hg/mL/min/kg	0.065 ± 0.026	0.060–0.070
LCWI	kg·min/m^2	6.6 ± 2.3	6.2–7.1
	mm Hg/mL/min/kg	17,045 ± 5393	15,957–18,132
LVSWI	g·min/m^2	76.7 ± 24.5	71.7–81.6
	mm Hg/mL/min/kg	199 ± 54	188–210
LVRPP	Beats/min mm Hg	9057 ± 2937	8465–9649
RCWI	kg·min/m^2	0.91 ± 0.41	0.83–0.99
	mm Hg/mL/min/kg	2353 ± 981	2156–2551
RVSWI	g·min/m^2	10.4 ± 3.9	9.6–11.2
	mm Hg/mL/min/kg	27.1 ± 9.1	25.2–28.9
RVRPP	Beats/min mm Hg	1247 ± 510	1144–1350
DO_2	mL/min/m^2	790 ± 259	737–842
	mL/min/kg	29.5 ± 8.8	27.7–31.3
VO_2	mL/min/m^2	164 ± 71	148–181
	mL/min/kg	6.0 ± 2.6	5.5–6.5
O_2 extrac	%	20.5 ± 5.7	19.4–21.7
VCO_2	mL/min/m^2	128 ± 46	114–136

Source: Haskins SC, Pascoe PJ, Ilkiw JE, Fudge M, Hopper K, Aldrich J. Reference cardiopulmonary values in normal dogs. *Comparative Medicine* 2005;55:158–163.

BW, body weight; BSA, body surface area; a, arterial; mv, mixed venous; A, alveolar; c, capillary; a–v, arterial–mixed venous; m, mean; A–a, alveolar–arterial; PCO_2, partial pressure of carbon dioxide; HCO_3, bicarbonate; BD, base deficit; PO_2, partial pressure of oxygen; SO_2, hemoglobin saturation with oxygen; Hb, hemoglobin; C, content; O_2, oxygen; CO_2, carbon dioxide; ven admix, venous admixture; HR, heart rate; ABPm, mean arterial blood pressure; CVP, central venous pressure; PAPm, mean pulmonary arterial blood pressure; PAOP, pulmonary artery occlusion pressure; CO, cardiac output; CI, cardiac index; SVI, stroke volume index; SVRI, systemic vascular resistance index; PVRI, pulmonary vascular resistance index; LCWI, left cardiac work index; LVSWI, left ventricular stroke work index; RCWI, right cardiac work index; RVSWI, right ventricular stroke work index; LVRPP, left ventricular rate pressure product; RVRPP, right ventricular rate pressure product; DO_2, oxygen delivery; VO_2, oxygen consumption; O_2 extrac, oxygen extraction; VCO_2, carbon dioxide production.

References

1. Powner DJ, Snyder JV. In vitro comparison of six commercially available thermodilution cardiac output systems. Med Instrum 1978;12:122–127.
2. Bilfinger TV, Lin CY, Anagnostopoulos CE. In vitro determination of accuracy of cardiac output measurements by thermal dilution. J Surg Res 1982;33:409–414.
3. Dyson DH, McDonell WN, Horne JA. Accuracy of thermodilution measurement of cardiac output in low flows applicable to feline and small canine patients. Can J Comp Med 1984;48: 425–427.
4. Norris SL, King EG, Grace M, Weir B. Thermodilution cardiac output—an in vitro model of low flow states. Crit Care Med 1986;14:57–59.
5. Sorensen MB, Bille-Brahe NE, Engell HC. Cardiac output measurement by thermal dilution: reproducibility and comparison with the dye-dilution technique. Ann Surg 1976;183:67–72.
6. Pelletier C. Cardiac output measurement by thermodilution. Can J Surg 1979;22:347–350.
7. Botero M, Kirby D, Lobato EB, Staples ED, Gravenstein N. Measurement of cardiac output before and after cardiopulmonary bypass: comparison among aortic transit-time ultrasound, thermodilution and noninvasive partial CO_2 rebreathing. J Cardiothorac Vasc Anaesth 2004;18:563–572.
8. Sakka SG, Reinahrt K, Meier-Hellman A. Comparison of pulmonary artery and arterial thermodilution cardiac output in critically ill patients. Intensive Care Med 1999;25:843–846.
9. Geodje O, Hoeke K, Lichtwarck-Aschoff M, Faltchauser A, Lamm P, Reichart B. Continuous cardiac output by femoral arterial thermodilution calibrated pulse contour analysis: comparison with pulmonary arterial thermodilution. Crit Care Med 1999;27: 2407–2412.
10. Della Rocca G, Costa MG, Coccia C, Pompei L, DiMarco P, Vilardi V, Pietropaoli P. Cardiac output monitoring: aortic transpulmonary thermodilution and pulse contour analysis agree with standard thermodilution methods in patients undergoing lung transplantation. Can J Anaesth 2003;50:707–711.
11. Osthaus WA, Huber D, Beck C, Winterhalter M, Boethig D, Wessel A, Sumpelmann R. Comparison of electrical velocimetry and transpulmonary thermodilution for measuring cardiac output in piglets. Paediatr Anaesth 2007;17:749–755.
12. Hamzaoui O, Monnet X, Richard C, Osman D, Chemia D, Teboul JL. Effects of changes in vascular tone on the agreement between pulse contour and transpulmonary thermodilution cardiac outpt measurements within an up to 6-hour calibration-free period. Crit Care Med 2008;36:434–440.
13. Thrush D, Downs JB, Smith RA. Continuous thermodilution cardiac output agreement with Fick and bolus thermodilution methods. J Cardiothorac Vasc Anesth 1995;9:399–404.
14. Watt RC, Loeb RG, Orr J. Comparison of a new non-invasive cardiac output technique with invasive bolus and continuous thermodilution. Anesthesiology 1998;89:A536.
15. Zollner C, Polasek J, Kilger E, Pichler B, Jaenicke U, Briegel J, Vetter H, Haller M. Evaluation of a new continuous thermodilution cardiac output monitor in cardiac surgical patients: a prospective criterion standard study. Crit Care Med 1999;27: 293–298.
16. O'Malley P, Smith B, Hamlin R, Nickel J, Nakayama T, MacVicar M, Mann B. A comparison of bolus versus continuous cardiac output in an experimental model of heart failure. Crit Care Med 2000;28:1985–1990.
17. Kothari N, Amaria T, Hegde A, Mandke A, Mandke NV. Measurement of cardiac output; comparison of four different methods. Ind J Thorac Cardiovasc Surg 2003;19:163–168.
18. Shoemaker WC, Appel PL, Kram HB, Waxman K, Lee TS. Prospective trial of supranormal values of survivors as therapeutic goals in high risk surgical patients. Chest 1988;94:1176–1186.
19. Ivanov R, Allen J, Calvin JE. The incidence of major morbidity in critically ill patients managed with pulmonary artery catheters: a meta-analysis. Crit Care Med 2000;28:615–619.
20. Binanay C, Califf RM, Hasselblad V, et al. Evaluation study of congestive heart failure and pulmonary artery catheterization effectiveness: the ESCAPE trial. JAMA 2005;294:1625–1633.
21. Hall JB. Searching for evidence to support pulmonary artery catheter use in critically ill patients. JAMA 2005;294(13): 1693–1694.
22. Pinsky MR, Vincent JL. Let us use the pulmonary artery catheter correctly and only when we need it. Crit Care Med 2005;33: 1119–1122.
23. Harvey S, Stevens K, Harrison D, Young D, Brampton W, McCabe C. An evaluation of the clinical and cost-effectiveness of pulmonary artery catheters in patient management in intensive care: a systematic review and randomised controlled trial. Health Technol Assess 2006;10: iii–iv, ix–xi, 1–133.
24. Friese RS, Shafi S, Gentilello LM. Pulmonary artery catheter use is associated with reduced mortality in severely injured patients: a National Trauma Data Bank analysis of 53,312 patients. Crit Care Med 2006;34:1597–1601.
25. Hori T, Yamamoto C, Yagi S, Lida T, Taniguchi K, Hasegawa T, Yamakado K, Hori Y, Takeda K, Maruyama K, Uemoto S. Assessment of cardiac output in liver transplantation recipients. Heptobiliary Pancreat Dis Int 2008;4:362–366.
26. Maarek HM, Holschneider DP, Harimoto J, Yang J, Scremin OU, Rubinstein EH. Measurement of cardiac output with indocyanine green transcutaneous fluorescence dilution technique. Anesthesiology 2004;100:1476–1483.
27. Mason DJ, O'Grady M, Woods P, McDonell W. Assessment of lithium dilution cardiac output as a technique for measurement of cardiac output in dogs. Am J Vet Res 2001;62:1255–1261.
28. Bealieu KE, Kerr CL, McDonell WN. Evaluation of a lithium cardiac output technique as a method for measurement of cardiac output in anesthetized cats. Am J Vet Res 2005;66: 1639–1645.
29. Corley KTT, Donaldson LL, Furr MO. Comparison of lithium dilution and thermodilution cardiac output measurements in anaesthetised neonatal foals. Equine Vet J 2002;34:598–601.
30. Kelso LA. Complications associated with pulmonary artery catheterization. New Horizons 1997;6:259–263.
31. Mathews L, Singh KRK. Cardiac output monitoring. Ann Cardiac Anaesth 2008;11:56–68.
32. deWaal EEC, Kalkman CJ, Rex S, Buhre W. Validation of a new arterial pulse contour–based cardiac output device. Crit Care Med 2007;35:1904–1909.
33. Dyson DH, Allen DG, McDonell WN. Evaluation of three methods for cardiac output determination in cats. Am J Vet Res 1985;46:2546–2552.
34. Noe FE, Whitty AJ, Davies KR. Simultaneous computer-calculated carbon dioxide and oxygen direct Fick and dye dilution measurements of cardiac output in dogs. Acta Anaesthesiol Scand 1981;25:12–16.
35. Haskins SC, Pascoe PJ, Ilkiw JE, Fudge M, Hopper K, Aldrich J. The effect of moderate hypovolemia on cardiopulmonary function in dogs. J Vet Emerg Crit Care 2005;15:100–109.

36. Day TK, Boyle CR, Holland M. Lack of agreement between thermodilution and echocardiographic determination of cardiac output during normovolemia and acute hemorrhage in clinically healthy, anesthetized dogs. J Vet Emerg Crit Care 2007;17: 22–31.
37. Teboul JL, Mercat A, Lenique F, Berton C, Richard C. Value of the venous–arterial PCO_2 gradient to reflect the oxygen supply to demand in humans: effects of dobutamine. Crit Care Med 1998;26:979–980.
38. Mahutte CK, Jaffe MB, Sasse SA, Chen PA, Berry RB, Sassoon CSH. Relationship of thermodilution cardiac output to metabolic measurements and mixed venous oxygen saturation. Chest 1993;104:1236–1242.
39. Piehl MD, Manning JE, McCurdy SL, Rhue TS, Kocis KC, Cairns CB, Cairns BA. Pulse contour cardiac output analysis in a piglet model of severe hemorrhagic shock. Crit Care Med 2008; 36:1189–1195.
40. Guzzi L, Jaffe MB, Orr JA. Clinical evaluation of a new noninvasive method of cardiac output measurement: preliminary results in CABG patients. Anesthesiology 1998;89:A543
41. Gunkel CI, Valverde A, Morey TE, Hernandez J, Robertson SA. Comparison of non-invasive cardiac output measurement by partial carbon dioxide rebreathing with the lithium dilution method in anesthetized dogs. J Vet Emerg Crit Care 2004; 14:187–195.
42. Durkin R, Gergits MA, Reed JF, Fitzgibbons J. The relationship between the arteriovenous carbon dioxide gradient and cardiac index. J Crit Care 1993;8:217–221.
43. Godje O, Hoke K, Goetz AE, Felbinger TW, Reuter DA, Reichart B, Friedle R, Hannekum A, Pfeiffer UJ. Reliability of a new algorithm for continuous cardiac output determination by pulse-contour analysis during hemodynamic instability. Crit Care Med 2002;30:52–58.
44. Bein B, Worthmann F, Tonner PH, Paris A, Steinfath M, Heddderich J, et al. Comparison of esophageal Doppler, pulse contour analysis and real-time pulmonary artery thermodilution for the continuous measurement of cardiac output. J Cardiothorac Vasc Anaesth 2004;18:185–189.
45. Chakravarthy M, Patil TA, Jayaprakash K, Kalligudd P, Prabhakumar D, Jawali V. Comparison of simultaneous estimation of cardiac output by four techniques in patients undergoing off-pump coronary artery bypass surgery—a prospective observational study. Ann Card Anaesth 2007;10:121–126.
46. Pittman J, Bar-Yosef S, SumPing J, Sherwood M, Mark J. Continuous cardiac output monitoring with pulse contour analysis: a comparison with lithium indicator dilution cardiac output measurement. Crit Care Med 2005;33:2015–2021.
47. Linton NW, Linton RA. Estimation of changes in cardiac output from the arterial blood pressure waveform in the upper limb. Br J Anaesth 2001;86:486–496.
48. Cibulski AA, Lehan PH, Raju S, Keister TL, Bennet KR, Hellems HK. Pulmonary arterial pressure method for estimating the ventricular stroke volume. Am Heart J 1974;88:338–342.
49. Bourgeois MJ, Gilbert BK, Bernuth G, Wood EH. Continuous determination of beat-to-beat stroke volume from aortic pressure pulses in the dog. Circ Res 1976;39:15–24.
50. English JB, Hodges MR, Sentker K, Johansen R, Stanley TH. Comparison of aortic pulse-wave contour analysis and thermodilution methods of measuring cardiac output during anesthesia in the dog. Anesthesiology 1980;52:56–61.
51. Chen HC, Sinclair MD, Dyson DH, et al. Comparison of arterial pressure waveform analysis with the lithium dilution technique to monitor cardiac output in anesthetized dogs. Am J Vet Res 2005;66:1430–1436.
52. Cooper ES, Muir WW. Continuous cardiac output monitoring via arterial pressure waveform analysis following severe hemorrhagic shock in dogs. Crit Care Med 2007;35:1724–1729.
53. Duffy AL, Butler AL, Radecki SV, Campbell VL. Comparison of continuous arterial pressure waveform analysis with the lithium dilution technique to monitor cardiac output in conscious dogs with systemic inflammatory response synsdrome. Am J Vet Res 2009;70:1365–1373.
54. Romano SM, Pistolesi M. Assessment of cardiac output from systemic arterial pressure in humans. Crit Care Med 2002; 30:1834–1841.
55. Scolletta S, Romano SM, Biagioli B, Capannini G, Giomarelli P. Pressure recording analytical method (PRAM) for measurement of cardiac output during various haemodynamic states. Br J Anaesth 2005;95:159–165.
56. Hirschl MM, Kittler H, Woisetschlager C, Siostrzonek P, Staudinger T, Kofler J, Oschatz E, Bur A, Gwechenberger M, Laggner AN. Simultaneous comparison of thoracic bioimpedance and arterial pulse waveform–derived cardiac output with thermodilution measurement. Crit Care Med 2000;28:1798–1802.
57. Jellema WT, Wesseling KH, Groeneveid ABJ, Stoutenbeek CP, Thijs LG, van Lieshout JJ. Continuous cardiac output in septic shock by simulating a model of the aortic input impedance. Anesthesiology 1999;90:1317–1328.
58. Raaijmakers E, Faes TJC, Scholten RJPM, Goovaerts HG, Heethaar RM. A meta-analysis of three decades of validating thoracic impedance cardiography. Crit Care Med 1999;27: 1203–1213.
59. Albert NM, Hail MD, Li J, Young JB. Equivalence of the bioimpedance and thermodilution methods in measuring cardiac output in hospitalized patients with advanced, decompensated chronic heart failure. Am J Crit Care 2004;13: 469–479.
60. Kamath SA, Drazner MH, Tasissa G, Rogers JG, Stevenson LW, Yancy CW. Correlation of impedance cardiography with invasive hemodynamic measurements in patients with advanced heart failure: the bioimpedance cardiography (BIG) substudy of the ESCAPE trial. Am Heart J 2009;158:217–223.
61. Wynne JL, Ovadie LO, Akride CM, Sheppard SW, Vogel RL, Van De Water JM. Impedance cardiography: a potential monitor for hemodialysis. J Surg Res 2006;133:55–60.
62. Haryadi DG, Westenskow DR, Critchley LAH, Schookin SI, Zubenko VG, Beliaev KR, Morozov AA. Evaluation of a new advanced thoracic bioimpedance device for estimation of cardiac output. J Clin Monitoring Computing 1999;15:131–138.
63. Barin E, Haryadi DG, Schookin SI, Westenskow DR, Zubenko VG, Beliaev KR, Morozov AA. Evaluation of a thoracic bioimpedance cardiac output monitor during cardiac catheterization. Crit Care Med 2000;28:698–702.
64. Sherhag A, Kaden JJ, Kentschke E, Sueselbeck T, Borggrefe M. Comparison of impedance cardiography and thermodilution-derived measurements of stroke volume and cardiac output at rest and during exercise testing. Cardiovasc Drugs Therapy 2005;19:141–147.
65. Fellahi JL, Caille V, Charron C, Deschamps-Berger PH, Viellard-Baron A. Noninvasive assessment of cardiac index in healthy volunteers: a comparison between thoracic impedance cardiography and Doppler echocardiography. Anesth Analg 2009;108: 1553–1559.

66. Koobi T, Kaukinen S, Turjanmaa VMH. Cardiac output can be reliably measured noninvasively after coronary artery bypass grafting operation. Crit Care Med 1999;27:2206–2211.
67. Imhoff M, Lehner JH, Lohlein D. Noninvasive whole-body electrical bioimpedance cardiac output and invasive thermodilution cardiac output in high-risk surgical patients. Crit Care Med 2000;28:2812–2818.
68. Cariou A, Monchi M, Joly LM, Bellenfant F, Claessens YE, Thebert D, Brunet F, Dhainaut JF. Noninvasive cardiac output monitoring by aortic blood flow determination: evaluation of the Sometec Dynemo-3000 system. Crit Care Med 1998;26:2066–2072.
69. Perrino AC Jr, Harris SN, Luther MA. Intraoperative determination of cardiac output using multiplane transesophageal echocardiography: a comparison to thermodilution. Anesthesiology 1998;89:350–357.
70. Tibby SM, Hatherill M, Murdoch IA. Use of transesophageal Doppler ultrasonography in ventilated pediatric patients: derivation of cardiac output. Crit Care Med 2000;28:2045–2050.
71. Estagnasie P, Djedaini K, Mier L, Coste F, Dreyfuss D. Measurement of cardiac output by transesophageal echocardiography in mechanically ventilated patients. Comparison with thermodilution. Intensive Care Med 1997;23:753–759.
72. Wall PL, Rudison MM, Lazic T, Reidesel DH. Transesophageal monitoring of aortic blood flow during nonemergent canine surgeries. J Vet Emerg Crit Care 2002;12:1–8.
73. Arheden H, Stahlberg F. Blood flow measurements. In: Roos A de, Higgins CB, eds. MRI and CT of the Cardiovascular System. 2nd ed. Philadelphia: Lippincott ,Williams & Wilkins; 2006:71–90.
74. Kupinski MA, Hoppin JW, Krasnow J, Dahlberg S, Leppo JA, King MA, Barrett CE. Comparing cardiac ejection fraction estimation algorithms without a gold standard. Acad Radiol 2006;13: 329–337.
75. Haskins SC, Pascoe PJ, Ilkiw JE, Fudge M, Hopper K, Aldrich J. Reference cardiopulmonary values in normal dogs. Comparative Medicine 2005;55:158–163.