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Room 3B

Since the introduction of the Swan-Ganz catheter in 1971 ¹ measurement of cardiac output is still the mainstay for haemodynamic management of severely critically ill patients. Although results with respect to the effect of the pulmonary artery catheter (PAC) on outcome have been disappointing ² no true alternative to thermodilution methods seems currently to exist. None of the alternative methods to assess the required physiologic information has sufficiently validated, yet, or found its way to be established in routine clinical practice. Thermodilution measurement of cardiac output is therefore still the gold standard ³, regardless whether performed in the classical technique with a PAC or with a transpulmonary approach. The latter technique, where a cold bolus is injected into the right atrium and the thermodilution curve is measured in the arterial system, has more recently become increasingly popular in clinical practice, in particular in Europe.

In principle, several indicators can be used for indicator dilution measurements of cardiac output, namely “negative heat” (thermodilution), dyes (indocyanine green, ICG) and other in non-toxic substances, which can be traced in vivo such as lithium. Still, the vast majority of clinical measurements of cardiac output are performed with thermodilution. ICG and lithium are only of minor importance for cardiac output measurement.

BASICS OF INDICATOR DILUTION THEORY FOR MEASUREMENT OF CARDIAC OUTPUT

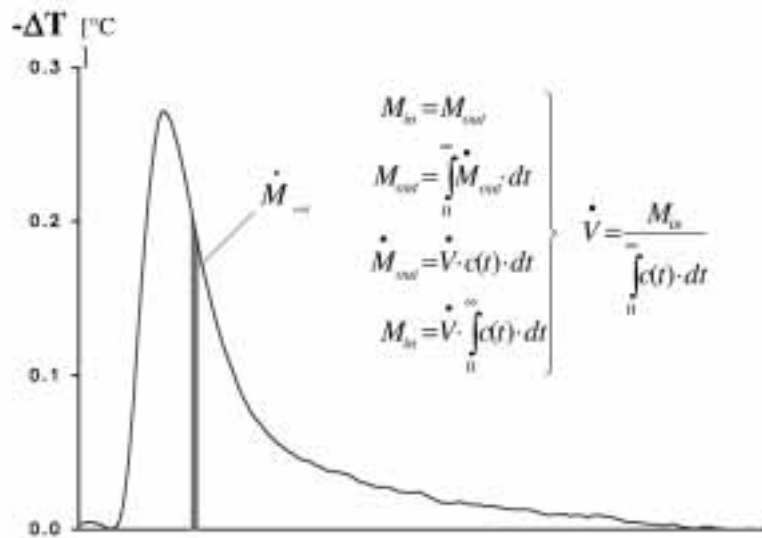
The basic principle for the measurement of cardiac output relies on the axiom of mass conservation: “What goes in must come out!” (Fig. 1). If a defined amount of a tracer M_{in} is injected into the right atrium, the same amount must emerge downstream (M_{out}), provided no significant loss of the tracer occurs ($M_{in} = M_{out}$). The amount of the injected tracer is usually known, i.e. a specific amount of a dye or a specific amount of “negative heat”. The amount of “negative heat” is the equal to the volume of the injected bolus multiplied by the difference between the injectate temperature and blood temperature:

$$M_{in} = V_{inj} \cdot (T_{blood} - T_{inj})$$

For measurements of cardiac output the concentration time course of the tracer is measured at a downstream site. Since the amount of a substance dissolved in a fluid is nothing else than the volume multiplied by its concentration, the amount passing the measurement site at each time interval is the product of the concentration ($c(t)$) and the volume which has passed the measurement site in the same time interval. However, volume per time interval is flow (V), and in the case of an injection into the right atrium and a measurement site downstream of the right heart (which acts as an mixing chamber) the flow represents the entire cardiac output. In vivo, the bolus is dispersed in the blood stream after injection into the right atrium and mixing by the right heart and the concentration therefore varies over time at the downstream measuring site. The result is a typical indicator dilution curve (Fig. 1). In order to retrieve the entire amount of the injected tracer bolus, the entire downstream concentration time course must be assessed and the total amount passing the measurement site is from by area under the indicator dilution curve (AUC) and cardiac output. Vice versa cardiac output results from the ratio of the amount injected (M_{in}) divided by the AUC.

Another problem of in vivo measurements is recirculation, which is typically visible in dye curves, but less evident in thermodilution curves. Usually the indicator dilution curves are therefore truncated before the occurrence of recirculation and mathematically extrapolated until infinity. Most cardiac output computers perform this extrapolation by fitting of an exponential decay to the downslope part of the indicator thermodilution curve between 70 and 30% of the peak height.

FIGURE 1



It is obvious, that this principle of measurement might work for the measurement of cardiac output, if the injection of the tracer is performed into the right atrium and the measurement site is directly behind the right heart chamber, i.e. in the pulmonary artery mainstem, where the entire cardiac output is passing by. However, in clinical practice measurement sites are located further downstream in bronchial arteries or even on the arterial site in a femoral artery. Isn't there any loss of the tracer due to branching of the vascular tree? Intuitively the clinician might think, that a quantitative measurement might work only, if the entire quantity of the tracer is passing the measuring site. Fortunately, this is not true. Branching of vessels naturally divides the blood flow into the respective flow fractions, however, the concentration of substances within the blood stream are not affected. The concentration remains the same before and after a branching point. Thus, with several branching points in series in the circulation the indicator dilution curve might become dispersed, i.e. flatter and longer, but the area under the curves is the same, regardless of sampling location or measuring site.

Nevertheless, loss of indicator was a concern, in particular with the transpulmonary thermodilution technique. Theoretically, "negative heat" could be lost via the respiratory system during pulmonary passage of the cold bolus. However, it has been demonstrated by Bock et al. (Lit) in animal experiments, as well as by von Spiegel and Hoefl in patients (Lit), that the heat loss during pulmonary passage is minimal and that it can be neglected in clinical practice.

WHEN IS MEASURING OF CARDIAC OUTPUT INDICATED?

After the landmark paper of Connors (Lit), it became questionable whether there is any indication to measure cardiac output in patients, at all. The observation that critically ill patients with a pulmonary artery might have a worse outcome than those without was a severe disappointment for the intensive care community. In fact, up to date there is no clear cut, evidenced based indication for the application of the pulmonary artery catheter or measurement of cardiac output. Nevertheless, in certain situations measurement of cardiac output might be helpful. In principal, cardiac output always should be measured when more or less aggressive haemodynamic management of the patient is required:

1. Haemodynamic instability requiring large amounts of fluids and/or vasopressor support.
2. Signs of persistent tissue hypoxia, i.e. elevated lactate levels without tendency to resolve spontaneously
3. Sepsis or SIRS with circulatory failure
4. Sepsis and SIRS with organ failure
5. Respiratory failure requiring aggressive ventilation

PAC OR PiCCO®?

In many institutions the transpulmonary indicator dilution with a thermistor catheter in the brachial, axillary or (mostly) femoral artery, has become the preferred approach for enhanced haemodynamic monitoring due to several reasons:

1. Most patients require an arterial line, anyhow. The arterial thermistor catheter adds therefore very little invasiveness, if at all.
2. As opposed to the PAC, a volumetric index of the central filling of the circulation can be measured, such as intrathoracic blood volume (ITBVI) or global enddiastolic volume (GEDV). Moreover, extravascular lung water is measured as a valuable pathophysiologic parameter in patients with ARDS or other forms of pulmonary edema.
3. Measurements are easy to perform and intuitively understandable, in particular for young physicians in training.
4. Cardiac output and stroke volume variation as an additional index for the volume responsiveness of the patient are continuously monitored by pulse contour analysis of the arterial wave form.

Nevertheless, in some patients a PAC is still considered to offer specific advantages:

1. Patients, in whom pulmonary hypertension is a therapeutic problem, i.e. in all patients in whom therapeutic nitric oxide is indicated. These severely ill patients, typically suffering from ARDS, often are monitored by both, PAC as well as PiCCO®.
2. Patients arriving with PAC in the ICU, often after the cardiac surgery.

THERAPEUTIC GOALS

What are the therapeutic goals in clinical practice? The physiologic task of the cardiovascular system is to deliver a sufficient blood flow to the tissues and organs in order to maintain the respective oxygen and substrate demands. Intuitively, managing haemodynamics with the goal to achieve physiologically normal values seems reasonable. As a rule of the thumb this means:

Arterial perfusion pressure:	MAP > 70 mmHg
Cardiac output:	CI > 3.0 l min ⁻¹ m ⁻²
Stroke Volume:	SVI > 40 ml m ⁻²
Volume status:	
a) Global Enddiastolic Volume	GEDV > 680 ml m ⁻²
b) Intrathoracic Blood Volume	ITBVI > 850 ml m ⁻²
c) Stroke volume variation	SVV < 10%
Extravascular Lung Water	EVLWI < 7.0 ml kg ⁻¹

VOLUME

Always, optimization of volume status comes first. Since catecholamines and vasopressors are known to have detrimental effects on splanchnic perfusion as well as on the blood flow distribution in the microcirculation, hemodynamic management should aim at as minimal use of vasopressors as possible. Conversely, as much as possible volume should be given in order to save catecholamines and vasopressors. Of course, the crucial question is how much is possible? In general, a patient with an ITBVI of less than 850 ml m⁻² or an GEDV of less than 680 ml m⁻² should be considered hypovolemic. The type volume to be given, depends on other criteria, such as haemoglobin content, etc.. The endpoint of volume resuscitation varies from patient to patient. In patients with pulmonary edema the tendency will clearly be, to keep them more on the “dry side”. On the other hand, patients with sepsis often benefit from much higher intravascular volumes. Beside other clinical criteria (urine output, time course of lactate levels) also stroke volume variation might serve as an index of volume responsiveness⁴ Extravascular lung water is another limiting parameter, which might serve as a safety parameter. Application of volume is most likely safe, as long as EVLW is not increased.

VASOPRESSORS & CATECHOLAMINES

If a sufficient cardiovascular performance cannot be achieved by volume resuscitation alone, vasopressors and catecholamines might be required. A basic principle is, that “flow” is more important than “pressure”. Another basic principle is, that tachycardia should be avoided, if possible. Thus, the major goal is to achieve a decent stroke volume, i.e. a stroke volume index higher than 40 ml m^{-2} . Optimizing stroke volume following optimization of cardiac filling is equivalent to targeting at a sufficient ejection fraction. Interestingly, the ejection fraction has also been demonstrated from a theoretical point to be an ideal target value for optimization cardiovascular performance. In a very interesting and sophisticated “Medical Intelligence Article” Robotham et al.⁵ very nicely analysed the physiological relevance of the ejection fraction in terms of arterio-ventricular coupling and under the aspect of mechanical efficiency of myocardial performance. They came to the conclusion that “... ejection fraction appears to be a highly efficient and integrated measure of the entire cardiovascular systems’ ability to cope with abnormalities in any or all of the three critical variables that determine ventricular performance – preload, afterload, and contractility.”

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