Cardiac Output Monitors

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Learning Objectives

Understanding of the historical evolution of cardiac output monitoring in intensive care medicine; understanding the (historical) reasons, why cardiac output monitoring is still not used as routine monitoring in critically ill patients; overview of currently used technological concepts for bedside cardiac output monitoring.

22.1 Introduction

Cardiac output, i.e., the quantification of the blood flow that is generated by the heart, is by far the most important macrohemodynamic variable in the assessment of hemodynamic instable, critically ill patient. Although of course, also cardiac output can only be of significant help, if its values (and much more importantly its changes under therapy) are interpreted within the context of other hemodynamic and metabolic parameters, its assessment frequently determines and changes the direction of therapeutic interventions. This chapter will try to give an overview of the methodological and technical principles of cardiac output monitors (please see ◘ Table 22.1) and the impact of each of them on their clinical usability. It therefore tries to function as a bracket around the following chapters, where each of the methods that are presently available is separately described and discussed in depth.

22.2 Historical View Back

Historically, cardiac output monitors have not been used routinely in critically ill patients. And also, when looking at recent data from European ICU's, cardiac output monitoring is performed only in a small minority of our patients [1]. The reason for that – and the

◘ **Table 22.1** Clinically available technologies for cardiac output monitoring

Measurement technique	Description
Indicator dilution	Application as pulmonary artery thermodilution or transpulmonary thermodilution Serve as clinical gold standard for CO measurement Additional parameters provided: right ventricular ejection fraction, right ventricular end-diastolic volume (both for pulmonary artery thermodilution), global end-diastolic volume, extravascular lung water (both for transpulmonary thermodilution)
Doppler-derived blood flow measurement	Low invasiveness High user dependency Not suitable for long-term use
Pulse wave analysis	Low-intermediate invasiveness Not suitable for patients with arrhythmias Prone to artifacts Limited exactness; focus is in trending
Bioimpedance and bioreactance	Noninvasiveness Limited validity compared to clinical gold standard

overwhelming interest in blood pressures – is easy to explain; for many decades, the assessment of blood flow was technically simply too difficult and cumbersome for a routine use. Methods derived in the nineteenth century were based on the principle of indicator dilution. Salt solutions or dyes, injected into the venous system and then detected in arterial blood samples, served as indicators [2]. Not only the fact that handling these indicators properly was not really user-friendly, but also the detection of downslope concentrations was not possible at the bedside, but needed additional technical and human resources. Similarly, the CO2 rebreathing method based on the Fick principle did not reach the clinical routine use due to inhomogeneity of measurement results and technical complexity.

Thus, "monitoring" by its principle meaning was simply not possible with these methods. Other technical principles, such as the arterial pulse contour analysis (or pulse wave analysis), which were also described already more than 100 years ago, had theoretically already overcome those problems of "discontinuity" and "time delay"; however, also their practical usability remained theory, until the evolution of computerization within the 1980s and 1990s of the last century, making the automated use of calculation algorithms at the bedside possible [3, 4]. However, the "historical breakthrough" for clinical cardiac output monitoring was made by the technical modification of an indicator dilution principle: Thermodilution within the pulmonary artery, using the pulmonary artery catheter (PAC), or named after their pioneers William Ganz and Jeremy Swan the "Swan-Ganz catheter," became a technique, which allowed quantifying cardiac output in clinical routine at the bedside [5]. However, also the PA catheter remained an exotic monitoring tool within the ICUs with its use restricted to a small group of highly complex critically ill patients. This is because as a highly invasive method, its use is of course associated with a certain risk profile, but it is even more problematic that, for its implementation and its proper use, this method is still dependent on the presence of highly skilled personnel – it is simply not an easy "plug and play device" [6, 7]. Amelioration of these method immanent drawbacks and at least a small increase in the use of thermodilution cardiac output monitoring outside the small community of PAC enthusiasts came with the availability of transpulmonary thermodilution devices in the mid-1990s [2]. However, the limitation of discontinuity and non-automatization remained also here.

The next big milestone and opportunity for cardiac output monitoring to become much more integral part of bedside monitoring as a continuous variable were the clinical implementation of ultrasound and in particular echocardiography. Besides manifold other highly important diagnostic opportunities, which make this technology indispensable from the ICU, echocardiography-based cardiac output determination seemed to fulfill the criteria such as "real-time," easy-to-use," and "noninvasive" [8]. However, its drawbacks of being user-dependent, noncontinuous, and time- (and personnel-) consuming have prevented this technology to become a real "cardiac output monitor." This is different with the application of Doppler by miniaturized transnasal esophageal probes, which has found its place as cardiac output monitoring for short-term use in perioperative medicine [9].

In parallel to this evolution of ultrasound, the historical technique of pulse wave or pulse contour analysis has become available within the 1990s of the last century. The principle, as Otto Frank, physiologist, and one part of the well-known "Frank-Starling mechanism" have described already in 1899, has remained the same until today: "Under certain circumstances, it might be possible to generate information of blood flow from the shape of the blood pressure curve." However, now analysis has become automated and available at the bedside, and the principle has been transformed from central arteries and invasively deducted signals to peripheral pulse signals, which are assessed completely noninvasive, using even not only the arterial pressure signal but also other signals, such as the photoplesmythographic pulse signal [10].

22.3 What Do We Need from a Cardiac Output Monitor?

Clinical utility of cardiac output monitors is defined by the following modalities: (a) Measurements need to be reliable, i.e., exactness of measurements should be high in terms of bias and precision; (b) the method should be noninvasive in order not to place additional risks to the patient because of the measurements; (c) the method should provide continuous and real-time measurements; (d) it should be automated in order to save human resources; (e) if not automated, it should be as user-independent as possible in order to minimize inter-user discrepancies in results; and (f) it should be easy to implement and use in order to reach a high degree of acceptance in daily clinical practice.

22.4 Methods of Measurement

So up today, the following principle methods are available for cardiac output monitoring.

22.4.1 Indicator Dilution

This comprises pulmonary artery thermodilution using a sensor-tipped PAC; transpulmonary thermodilution with a femoral, axillary, or brachial sensor-tipped arterial catheter; and lithium dilution, again with a peripheral sensor-tipped arterial catheter. The common basic principle is that a known amount of indicator is brought as a bolus within the circulation, and further downstream, its concentration over time is measured. The faster the blood flow is, the faster is the rise, as well as the decline of the indicator concentration downslope. All these technologies, and for historical reasons in particular the pulmonary artery thermodilution are seen as the "clinical gold standard" [2]. So determination of absolute values of cardiac output, also repetitive over time, is most reliable using one of those techniques. However, bolus application already implies the most prominent disadvantage; all indicator dilution techniques, also when bolus application is automated, remain intermittent, discontinuous measurement techniques.

22.4.2 Doppler-Derived Blood Flow Measurement

Doppler-based cardiac output measurements can be achieved by transthoracic, transesophageal echocardiography or using miniaturized esophageal Doppler probes [8, 9]. The principle is as follows: With the use of the Doppler effect, the flow profile of the ultrasound-reflecting erythrocytes through a vascular structure is continuously assessed and quantified as a velocity-time integral. If now the vascular diameter (right/left ventricular outflow tract, descending aorta) is known (or estimated), stroke volume and thus cardiac output can be continuously assessed. The striking advantages are the noninvasiveness and the real-time/beat-to-beat assessment. However, all these techniques remain user-dependent and (with the exemption of esophageal Doppler) are only temporary snapshots – echocardiography is by nature not a monitoring modality.

22.4.3 Pulse Wave Analysis

If the elastic properties of the arterial wall remain constant, then the integral of the systolic portion of the arterial pressure curve is directly correlated to the left ventricular stroke volume. This is the basic assumption of most arterial pulse contour algorithms currently in use [11]. Its use, which was initially just assumed to be "clinically valid enough" in central arteries, i.e., the aorta, has been extended to pressure tracings derived from peripheral arteries, both measured invasively and noninvasively, as, for example, with volume clamp technology [12]. The advantage of all of those variants of pulse contour analysis is that it is an automated, beat-by-beat, continuous, and user-independent measurement technique. However, on the other side, the exactness of arterial pulse contour analysis, compared to the clinical gold standards of thermodilution, in particular in terms of absolute values, is limited. Further, this technique is quite sensible for measurement errors produced by artifacts within the raw signal (pressure curve).

22.4.4 Bioimpedance and Bioreactance

Recently, two other noninvasive cardiac monitoring technologies were clinically introduced, which both use the assessment of changes in electrical conductivity within the thorax to quantify stroke volume and cardiac output [13]. The principle idea behind it is that if intrathoracic blood volume is changing due to blood ejection into the circulation, accordingly, electrical conductivity of a high-frequency but low-magnitude current, which is applied to the thorax via a skin electrode, is changing accordingly. Literally, stroke volume serves as an electrical contrast medium, which is continuously assessed. The advantages of those methods are noninvasive, real-time, continuous, and automated monitoring. However, the most important drawback so far is the limited exactness of these technologies in comparison to the clinical gold standards of cardiac output monitors [10].

Take-Home Messages

Availability and applicability of cardiac output monitors have tremendously increased during the last two decades, making assessment and monitoring of this very central hemodynamic variable feasible theoretically in all patients on the ICU, which show signs of hemodynamic instability. Each method has its own profile of advantages and disadvantages in particular in terms of invasiveness versus exactness of results. However, the needs for the individual patients in intensive care differ: In patients where cardiac output monitoring is performed in order to preemptively avoid phases of hemodynamic instability and to routinely guide standard therapies, as in elective perioperative patients, automatization and low invasiveness dominate over exactness, whereas in the highly complex, hemodynamically instable, critically ill patient in shock, precision of measurement and the availability of other associated hemodynamic parameters have much higher importance.

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