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Pulse waveform hemodynamic monitoring devices: recent advances and the place in goal-directed therapy in cardiac surgical patients

Adham Hendy, Şerban Bubenek

Carol Davila University of Medicine and Pharmacy, Bucharest, 1st Department of Cardiovascular Anaesthesia and Intensive Care, C.C. Iliescu Emergency Institute for Cardiovascular Diseases, Bucharest, Romania

Abstract

Hemodynamic monitoring has evolved and improved greatly during the past decades as the medical approach has shifted from a static to a functional approach. The technological advances have led to innovating calibrated or not, but minimally invasive and noninvasive devices based on arterial pressure waveform (APW) analysis. This systematic clinical review outlines the physiologic rationale behind these recent technologies. We describe the strengths and the limitations of each method in terms of accuracy and precision of measuring the flow parameters (stroke volume, cardiac output) and dynamic parameters which predict the fluid responsiveness. We also analyzed the place of the APW monitoring devices in goal-directed therapy (GDT) protocols in cardiac surgical patients. According to the data from the three GDT-randomized control trials performed in cardiac surgery (using two types of APW techniques PiCCO and FloTrac/Vigileo), these devices did not demonstrate that they played a role in decreasing mortality, but only decreasing the ventilation time and the ICU and hospital length of stay.

Keywords: minimally invasive monitoring, non-invasive monitoring, arterial pressure wave form technology, perioperative hemodynamic optimization by goal-directed therapy, cardiovascular surgery

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Introduction

The pulmonary artery flotation catheter (PAC) has been considered as the gold standard of hemodynamic monitoring for a long time and it still remains a useful device in situations when the knowledge of pulmonary artery pressure values (PAP), pulmonary capillary wedge pressure levels (PCWP) and oxygenation parameters are required [1]. Much has been changed since the PAC was first introduced by Swan and Ganz in 1970. Connors et al. [2] raised important questions regarding the value of PAC as a safe, accurate and precise tool in treating a variety of intensive care unit (ICU) patients. In this observational study the PAC was associated with an increased risk of mortality and increased resource use. A recent Canadian multicenter longitudinal randomized study has shown a 50% reduction in the rate of PAC use over 5 years [3] because PAC is invasive and is associated with various complications (infections, arrhythmias, thrombosis and pulmonary artery rupture) and financial costs [4]. The last decade was characterized by a growing interest in innovating, less invasive devices that could be substituted for the PAC. Some of these new techniques were integrated into appropriate protocols that guide the hemodynamic evaluation and the subsequent therapeutic interventions and it was proven that their optimal use can reduce the morbidity, the mortality and can improve the outcome in both surgical [5-6] and non-surgical patients [7]. These recent technologies

Adress for correspondence: Dr. Adham Hendy
Institutul de Urgenţă pentru Boli Cardiovasculare "C.C. Iliescu"
Şoseaua Fundeni, nr. 258
022322 Bucureşti, Romania
E-mail: adham.hendy@gmail.com

range from totally non-invasive to marginally less invasive procedures than the PAC.

Basic description of pulse waveform technology (arterial pressure waveform analyzers)

The method of calculating stroke volume (SV) from the contour of the arterial pressure waveform (APW) dates from the end of the nineteenth century but was brought back into daily clinical practice by the advancements in computer technology in the 1980s [8]. In 1899 Otto Frank described the circulation as a Windkessel (air chamber) model [9]: the fluid moves into elastic tubes because the heart acts as a pump used by the firemen (a pulsatile pump able to deliver a peripheral continuous flow) pumping fluid into the tubes through chambers containing air (not existing in humans). Because the tubes were completely filled with a non compressible fluid the author states that the air (being compressible) mimics the aortic distension or compliance. The main conclusion was that the flow (SV) could be calculated from the variation of pressure. This statement is true but it is not so easy to be applied into practice. In fact, during the cardiac cycle both volume and pressure change over time but the relationship between arterial pressure and volume (i.e., compliance) varies from individual to individual, and for any given individual compliance there are also variations as a nonlinear function of arterial blood pressure and sympathetic status. More than this, the pulse pressure (a parameter used to estimate the SV in many algorithms) is composed from antegrade waves that drive the forward flow as well as retrograde reflected waves that retard the forward flow. Since the first description of the Windkessel two-compartments model the researchers have developed our knowledge offering today various algorithms which are based on the APW analysis for the continuous measurement and monitoring of the SV continuously, in a beat to beat manner. Some of this apparatus known as "pulse contour analyzers" (those produced by Pulsion Medical System – Germany and Edwards-Lifesciences – USA) are based on the measurement of the SV derived from the area under the systolic portion of the APW. The "pulse contour" technology uses the "Wesseling equation" (Equation 1): the contour of the APW is dependent on SV and the SV can be estimated from the integral of the change in pressure over time considering the area of the systolic part of the curve [10].

$$\text{SV= Systolic area / Impedance} = \frac{\int_{t0}^{t1} \frac{dP}{dt}}{Z}$$

where: t0/t1 for dP/dt: the integral of the change of the pressure from end diastolic t0 to end systolic t1, Z: impedance of the aorta

Karel Wesseling and co-workers went further and introduced the 3 element Windkessel model, an algorithm which uses the systolic area but with correction factors for the impedance: the arterial compliance and the systemic vascular resistance (SVR). Obviously we need to know the value of the total impedance and this value can be either calculated during a calibration phase or only estimated mainly based on the patient's demographic data.

Today two types of APW analyzers are commercially available: "calibrated" systems (they require a central venous catheter – CVC and a peripheral thermistor tipped specific arterial catheter in order to use the trans-pulmonary thermodilution – TPTD measurement of the cardiac output – CO as initial calibration) and "uncalibrated" systems which have an autocalibrating proprietary algorithm based on the patients' characteristics. The LiDCO technology is a peculiar calibrated APW analyzer because it does not use the pulse contour method to measure the SV but a special arterial pulse power analysis method.

Calibrated pulse waveform analyzers

The PiCCO technology (Pulsion Medical Systems – Germany)

This technology emerging in the early 1990s was the first calibrated APW analyzer introduced into clinical practice under the name of PiCCO but nowadays we use already the second or the third generation of such apparatus namely: PiCCOplus and PiCCO$_2$. The initial calibration consists of measuring the CO by TPTD method. A 10-15 ml cold 0.9% saline bolus is injected through a CVC and the change in the temperature overtime will be measured and analyzed by a thermistor tipped catheter inserted in a central artery (femoral, axillary, brachial, radial) [11]. The CO is calculated using Stewart Hamilton thermodilution equation (Equation 2).

$$CO = \frac{(Tb - Ta) \times Vi \times K}{\int \frac{dT}{dt}}$$

where: Tb = temperature before injection, Ta = temperature after injection, Vi = volume of injectate, K = constant, dT/dt = change in temperature per change in time

Many studies have proved that the TPTD-CO values agree very well with the PAC-CO values in a big variety of patients: cardiology, cardiac-surgery, liver transplant, burns, paediatrics, acute respiratory distress syndrome [12-21]. The calibration serves to measure not only the CO but also the individual aortic compliance (Cp) which will be further used to measure continuously beat by beat the SV as shown below (Equation 3):

$$SV = cal \cdot HR \int \left(\frac{p(t)}{SVR} + C(p) \cdot \frac{dp}{dt}\right) dt$$

where: Cal = patient specific calibration factor (determined by TPTD), S = area under systolic part of the pressure curve, Cp = individual aortic compliance, dP/dt: shape of pressure curve

As seen in the equation above (a second generation algorithm applied by Pulsion), the SV is measured beat by beat using the thermistor tipped catheter inserted in the artery assuming that the area under the systolic part of the arterial pressure waveform is related to the SV by aortic impedance but the algorithm itself is much more complicated than the original Wesseling equation (SV = systolic area / impedance) including also SVR. In conclusion, once calibrated by TPTD, the system is able to measure continuously (in fact as a mean for every 12 seconds) the SV, cardiac index (CI), CO, stroke volume variations (SVV) and pulse pressure variations (PPV). The SV, CI and CO measured by PICCO pulse contour analysis were shown to agree well with the values obtained with PAC [22-28]. The calibration should be repeated every 8 hours in hemodynamically stable patients and approximately every 1 hour in unstable patients or when vasoactive therapy is given [29-30]. The TPTD also offers the direct measurement of other parameters needed for a comprehensive evaluation of the hemodynamic status: the intrathoracic thermal volume (ITTV), the pulmonary thermal volume (PTV) and the global end-diastolic volume (GEDV = ITTV-PTV). Based on the relationship between GEDV and intra-thoracic blood volume (ITBV = 1.25 × GEDV) the apparatus will calculate the value of the extravascular lung water (EVLW = ITTV-ITBV) and the pulmonary vascular permeability index (PVPi = EVLW / PBV). A variety of studies have validated the accuracy and the precision of the PiCCO technology in cardiac surgical patients stable or not [31-34], but to date the PiCCO technology was used only in two goal-directed therapy (GDT) randomized control trials (RCT) in cardiac surgical patients. The first study was performed in perioperative off-pump coronary artery bypass surgery (OPCAB) with the following targets in the PiCCO group: ITBVI = 850-1000 ml · m^{-2}, MAP = 60-100 mmHg, HR < 90 beats · min^{-1}, Hb ≥ 8 g · dl^{-1}, CI ≥ 2 l · min^{-1} · m^{-2} and $ScvO_2$ > 60%. Unfortunately, achieving these complicated targets did not demonstrate a decrease in mortality or morbidity but only a decrease in the ICU stay and hospital stay respectively, in comparison with the control group [35]. Neither a second GDT-RCT study in valve repair surgery ($PiCCO_2$ versus PAC, with the following goals in the $PiCCO_2$ arm: GEDVI 680-850 ml · m^{-2}, EVLWI < 10 ml · kg^{-1}, MAP = 60-100 mmHg, CI > 2 l · min^{-1} · m^{-2}, DO_2I = 400-600 ml · min^{-1} · m^{-2} and $ScvO_2$ > 60%) found a decrease in mortality or morbidity but only a reduced period of postoperative mechanical ventilation in the $PiCCO_2$ group [36].

EV1000 / VolumeView (Edwards Lifesciences – USA)

The VolumeView technology is a part of the EV1000™ platform and it works in a similar manner with PiCCO: it uses the TPTD for the initial measurement of CO value and calibration of the system (always using the Stewart Hamilton equation). Once calibrated, the VolumeView sensor will measure SV beat by beat based on a complex proprietary "combination" algorithm which combines the conventional approach (the SV value is direct proportional with the area under the systolic part of the APW and inversely with the impedance) with an advanced wave shape approach (analysis of the pressure waveform of the entire heart cycle). The system obviously needs a CVC and a thermistor tipped specific catheter into the femoral artery (for calibration by TPTD) and the VolumeView sensor. Like the PiCCO systems this technology provides the operator important hemodynamic variables such as CO, CI, SV, SVV, PPV, GEDV and EVLW. The GEDV and the EVLW values are calculated based on the thermodilution curve but using different equations in comparison with those used by PiCCO. Validation studies confirmed the agreement and the interchangeability between the hemodynamic variables (CO, GEDV and EVLW) measured by TPTD with the new VolumeView system and the PiCCO system [37-39]. The system has not yet been included in any study focusing on GDT in cardiac surgery.

LiDCOplus (LiDCO Ltd, Cambridge, UK)

The LiDCOplus system is different from the PiCCO and EV1000 as it does not use the pulse contour method to measure the SV but a pulse power analysis based on the principle of the conservation of mass (power), assuming a linear relationship between net power and net flow inside the vascular system. The system combines lithium dilution as calibration method with a proprietary algorithm (PulseCO system autocorrelation) for an APW analysis in order to track the continuous changes in the SV detected by a specific sensor connected to a standard arterial line [40]. The technique was described in 1993 [41] and the calibration method is represented by the lithium dilution (a lithium dilution sensor with a lithium selective electrode). This electrode calculates the voltage change by using the Nernst equation in the flow through the transducer which is connected to an arterial line and is used to detect lithium. Isotonic lithium chloride 150 mM, 0.002-0.004 mmol · kg^{-1} is injected through a central or even a peripheral venous line [42]. A concentration time

curve is created and the CO is measured using the following formula (Equation 4):

$$CO = \frac{LiCL \times CO}{Area \times (1 - PCV)}$$

where: LiCL = dose of lithium chloride in mmol, Area = is the area under the lithium time dilution curve, PCV = packed cell volume which derived from haemoglobin concentration

After the calibration, the continuous SV measurement is performed in three phases: the first phase is transforming the arterial pressure waveform into a volume time waveform, then the system will derive SV and cardiac cycle duration and eventually the nominal SV is calculated. The need for frequent blood samples, the influence of non-depolarizing neuromuscular blockers are the main disadvantages of this technology. The accuracy of the device was seriously questioned during inaccurate sodium and haemoglobin measurements (each 1 $g \cdot dl^{-1}$ difference in haemoglobin concentration results in 4% difference in the CO measurement) [43]. Meantime, the validation studies confirmed that LiDCO is a sensitive minimally invasive beat-to-beat monitor of the SV and CO and it also offers some dynamic parameters of fluid responsiveness (SVV, PPV) which have shown to be able to predict the fluid responsiveness both during OPCAB and conventional coronary artery bypass graft (CABG) surgery [44-47]. The system was used for early post-operative GDT strategy in major abdominal and vascular surgery (the main targets in the study arm were: increase SV > 10% with fluids and $DO_2I > 600$ $ml \cdot min^{-1} \cdot m^{-2}$ with fluid and/or dopexamine) [6] with interesting results: reductions in post-operative complications and duration of hospital stay in GDT patients. In contrast, LiDCOplus was never used in GDT protocols addressed to cardiac surgical patients.

Uncalibrated pulse waveform analyzers

FloTrac/Vigileo (Edwards Lifesciences – USA)

This system uses the arterial pressure waveform to measure the CO detected through a proprietary transducer (FloTrac) attached to a standard arterial line connected to the Vigileo monitor. The system does not need to be calibrated with an indicator or bolus of cold saline because this technology is based on the assumption that the SV is proportional to pulse pressure and the aortic impedance can be estimated using a sophisticated algorithm (based on gender, age, height, weight). During the last 10 years the SV algorithm was under continuous modifications aiming at improving its accuracy and precision: till now four software generations were developed. The first generation software used an algorithm based on the patient's demographic data (age, sex, weight and height) and a data base of CO measured by PAC in different clinical conditions correlated with the standard deviation of pulse pressure measured over 20 seconds window. The second generation software (1.07 or later) was designed to perform a self-calibration every minute. The third generation software (3.0 or later) which uses a dynamic tone technology and more physiological variables demonstrated an improved accuracy in cardiac surgical patients [48], in liver transplant [49] and in general surgery [50]. Because of the unreliability of the third generation software to track the changes in CI with vasopressors administration [51] the fourth generation software (version 4.00) was developed based on a new correction factor for acute changes in SVR. Despite these developments a recent study [52] performed in cardiac surgical patients demonstrated that the CO values measured by the fourth-generation software still evidenced an unacceptable discrepancy in comparison with PAC-CO values. In contrast, the trending ability of tracking the CO after vasopressor administration was greatly improved [52]. Being easy to use and measuring also the SVV the system was widely used with mixed results in terms of accuracy and precision in different patient populations. Regarding the cardiac surgical patients, the performance of FloTrac/Vigileo, PiCCOplus, and Vigilance CCO in CO measuring were comparable when tested against intermittent thermodilution in elective cardiac surgery [53]. In comparison with PAC the FloTrac/Vigileo was proved to be a reliable method for CO assessment both during CABG surgery [54] and after elective cardiac surgery [55] but remains sensitive to changes in vascular tone [56]. Newer studies have emphasized that the system is not accurate in cardiac surgical patients with low CO (especially when CI < 2.2 $l/min/m^2$) and in those with low ejection fraction (< 40 %) [57-58].

In CABG patients FloTrac derived SVV predicted fluid responsiveness with an acceptable sensitivity and specificity [59]. In elective cardiac surgery SVV assessed using FloTrac /Vigileo and PiCCOplus exhibited similar performances but the FloTrac-SVV was observed to have a lower threshold value than the PiCCOplus-SVV (10% versus 13%) [60]. In comparison with LiDCOplus, in a study on post-CABG patients the SVV values offered by the two systems were significantly different, the two methods being not interchangeable [61]. Since its introduction, the performance of uncalibrated FloTrac/Vigileo in terms of accuracy and precision of the measured CO has much improved particularly in hypodynamic and normodynamic patients but the trending capacity is still affected by changes in the vascular tone [62]. The only one GDT study in postoperative cardiac patients

which used FloTrac/Vigileo (the targets in the FloTrac arm were: CI = 2.5-4.2 l · min^{-1} · m^{-2}, SVI = 35-60 ml/beat · m^{-2}, SVRI = 1500-2500 dyn · s · cm^{-5} · m^{-2}, DO_2I = 450-600 l · min^{-1} · m^{-2}, $ScvO_2$ > 70%, SVV < 10% by giving fluid, inotropes, vasodilators) demonstrated decreased ventilation time and decreased ICU and hospital stay in the FloTrac group in comparison with the control group but no change in mortality [63].

LiDCOrapid (LiDCO Ltd, Cambridge, UK)

The LiDCOrapid and LiDCOplus use the same proprietary algorithm tracking the continuous change on the SV but LiDCOrapid instead of using the lithium dilution technique as a calibration method uses in vivo derived nomograms (based on age, height, and weight) for SV and CO estimation. The system is easy to set up (1 minute) with the use of only a standard arterial line and any transducer kit and will also offer to the clinician many other important hemodynamic parameters as: SVV, PPV, SVR. Despite the initial enthusiastic approach, LiDCOrapid failed to demonstrate a good correlation for SV values when compared with the PiCCO pulse contour [64] or transesophageal Doppler [65]. Regarding the ability of the LiDCOrapid-SVV to predict the fluid responsiveness, some studies performed in high risk vascular surgery [66] and in cardiac surgery [67] confirmed that this parameter is an adequate predictor of the CO response to fluid administration. LiDCOrapid was never used in GDT protocols in cardiac surgery but in obstetrics where the main advantages were less maternal hypotension and much less neonatal hypercapnia and hypoxemia in the GDT group than in the control group [68].

ProAQT/ PulsioFlex (Pulsion Medical Systems, Germany)

Pulsion medical recently introduced ProAQT technology (as part of the PulsioFlex platform) which offers a minimally invasive approach (very similar to FlowTrac/Vigileo) to patient hemodynamics with a standard arterial line (radial) and a specific sensor (ProAQT sensor) on the basis of pulse contour analysis with a proprietary algorithm without calibration. The PulsioFlex platform can be calibrated externally (against echocardiography for example) but also upgraded with a PiCCO module and will become a TPTD-calibrated system. The ProAQT technology is able to estimate beat by beat the SV and to calculate the CO, SVV, PPV and SVR. The preliminary results of a multi-center validation study on unstable critically ill patients indicated that the CI can be reliably monitored with PulsioFlex technology which was also able to keep track of changes in CI [69]. In a recent study, when compared with Vigileo in critically ill patients, ProAQT was better for tracking norepinephrine-induced changes in CI, equal to Vigileo for tracking fluid-induced changes in CI and inferior to Vigileo™ for estimating the absolute values of CI [70]. In CABG patients the CO derived by ProAQT sensor showed a sufficient accuracy compared to TPTD [71] but in OPCAB surgery the results were unsatisfactory if the system was not calibrated externally [72]. A GDT protocol based on ProACT was applied in major non-cardiac surgery (the targets in the ProAQT group were: PPV < 10 %, CI > 2.5 l · min^{-1} · m^{-2}, MAP > 65 mmHg, manipulated by giving fluids, inotropes or vasopressors) and did not find significant differences between the protocol and the control group in terms of morbidity, mortality or length of stay in ICU [73]. The Pro ACT was also used in a GDT protocol in abdominal surgery (general, gynecological and urological patients) with the main targets represented by a PPV < 10 %, a CI > 2.5 l · min^{-1} · m^{-2} and a MAP > 65 mmHg, manipulated by giving fluids, inotropes or vasopressors, with promising results: a decrease in postoperative complications (infections included) in the study group [74].

MostCare / PRAM (Vytech Health, Padova, Italy)

MostCare technology is a non-calibrated, mini-invasive method of hemodynamic monitoring (any arterial line connected to any transducer, no dedicated disposable) based on the PRAM algorithm (pressure recording analytical method). PRAM analyses the whole arterial pressure waveform (both systole and diastole) beat to beat, with sampling rate of 1000 Hz (in comparison with 100 Hz in other pulse contour devices) and automatically detects all significant arterial wave's points: systolic and diastolic points, dicrotic notch and all points of instability.

PRAM as another pulse contour method is based as on the principle that in the arteries the volume changes mainly because of the radial expansion of the vessels in response to pressure variations during the cardiac cycle. In distinction with other pulse contour methods, PRAM is also based on the physics theory of perturbations: a physical system under the effects of a perturbing factor tends to react in order to re-acquire its own stability [75]. According to this principle PRAM will measure the whole systolic area under the pressure curve (pulsatile and continuous) instead of measuring only the pulsatile part of the pressure curve as others pulse contour systems. SV is calculated from pulsatile and continuous areas divided by the impedance Z(t) which is obtained directly (requires no other predicted data apart from the expected MAP) from the morphological analysis of the pressure waveform (Equation 5) [76, 77].

$$SV = \frac{A}{Z(t)} = \frac{A}{(P/t) \times K}$$

where: A = the whole systolic area below the pressure curve, Z(t) = total impedance = arterial impedance + arterial compliance + SVR, K = the dimensional factor inversely related to the instantaneous acceleration of the vessel cross-sectional area (cm/sec^2 × cm^2), P/t (mmHg/sec) = the analytical description of the pressure wave profile as changes in pressure (P) with time (t) along each cardiac cycle

MostCare technology measures continuously not only the SV, CI and CO but also other important hemodynamic parameters: SVV, PPV, SPV, dP/dt max. Since MostCare uses an algorithm of calculation highly dependent on a very detailed arterial waveform analysis (point by point) intrinsic (aortic dissection, arterial compression, atherosclerotic plaques near the tip of the catheter, etc.) or extrinsic (air bubble, resonance phenomenon) disturbances will lead to incorrect hemodynamic measurements. Giomarelli et al. [78] demonstrated in stable CABG patients (at different stages from induction to postoperative ICU) a good agreement between PRAM-CO and PAC-TD CO measurements but more recent studies did not confirm at all this relationship [79].

A good correlation with PAC-CO was also found in sinus rhythm unstable patients after cardiac surgery with ongoing high doses of inotropic drugs for low cardiac output syndrome [80-81] but PRAM did not compare well with thermodilution in unstable patients with atrial fibrillation [82].

ClearSight system (Edwards Lifesciences® – USA)

Currently, ClearSight is a part of the EV1000 platform (Edwards Lifesciences – USA) but it was released under the name of ccNexfin (BMEYE B.V. Amsterdam, The Netherlands). It uses a totally non-invasive continuous blood pressure measurement (based on the Finapres method) to measure the CO continuously. The input parameters are represented by the patient's age, height and weight. The SV, CI and CO are calculated without external calibration although it can be calibrated externally from another monitoring system. There are three major phases in the SV and CCO measurement: measurement of continuous finger BP by the photoelectric photo-plethysmography and volume clamp method, transformation of the finger BP curve into a brachial artery waveform, calculation of the SV and CCO from the brachial arterial pressure pulse contour using a physiological, three-element, non-linear Windkessel model of the arterial input impedance (Zin). For measuring the continuous BP and SV the technology uses a cuff (wrapped around the middle phalanx of the 2nd, 3rd or 4th finger) which contains an infrared-LED emitter-detector pair dedicated to measure the diameter of the finger arteries. During the first phase the cuff inflates and deflates ("volume clamp") in order to keep the diameter constant throughout the cardiac cycle. The pressure needed to keep the diameter constant is continuously recorded generating a real-time pressure waveform. During the second phase a special algorithm will transform the finger BP waveform to a brachial artery BP waveform because the more proximal the measurement is, the less errors are probable. Eventually, during the third phase the SV is calculated using a pulse contour algorithm, dividing the pressure-time integral by Zin. The Zin value is calculated taking into account the patient's data and based on the three-element Windkessel afterload model (Zin = characteristic impedance + arterial compliance + peripheral resistance). ClearSight system uses an auto-calibration algorithm (Physiocal) that periodically recalibrates the system and a heart reference system which measures and corrects for the vertical height between the finger cuff and the heart. The technique is not applicable in low flow in the finger arteries, hypothermia, or peripheral oedema. ClearSight CO has been studied in cardiac surgical patients against PAC and PiCCO and has demonstrated a limited accuracy and precision and a high percentage error (weighted average of 41%) [83-91], but reliably track preload-induced changes in CO [92-94]. ClearSight was less accurate in patients with low CO, hypothermia and high SVR but performed better in patients with high CO [95]. It measures also SVV and PPV and these dynamic parameters (obtained totally non-invasive) were able to predict the fluid responsiveness in an accurate manner [96-97].

The limits of the pulse waveform technology

Despite the fact that the various types of apparatus described above uses various types of algorithms in order to estimate the SV, the APW method is based on the hypothesis that the SV value is directly proportional with the area under the systolic part of the APW and inversely with the impedance. In consequence, this technology is strongly influenced by aortic impedance, arterial compliance and SVR. The calibrated APW analyzers were proven to agree better when measuring the SV and CO in comparison with the PAC-CO and TPTD (in all categories of patients, cardiac surgical included) than the uncalibrated APW analyzers [22-28, 62].

On the other hand all these devices (calibrated or not) will be inaccurate and imprecise in patients with artefacts of the arterial waveform, arrhythmias, severe aortic valve regurgitation, aortic aneurysm, intracardiac and extra cardiac shunts, intra-aortic balloon

pump and in severe hemodynamic unstable conditions [9, 40, 41, 75, 98]. Regarding the SVV and PPV measured by the APW systems (invasive or not, calibrated or not), the studies performed in cardiac and non-cardiac surgical patients demonstrated that these are very good predictors of volume responsiveness [43-46, 59, 65, 66, 95, 96].

The place of APW monitoring devices in GDT in cardiac surgical patients

Despite the fact that the majority of the validation studies with regard to APW techniques were performed on cardiac surgical patients, the APW monitoring devices have been used only in three GDT-RCTs regarding the cardiac surgical patient: two studies with PiCCO technology [35, 36], and one study with FloTrac/Vigileo [63]. On the other hand, in cardiac surgical patients only another four RCT focused on GDT were published: two of these studies used PAC [99, 100] and two used esophageal Doppler monitoring [101, 102] in the study arm. None of these seven GDT-RCT (all were single-centered, less than 1,000 patients studied in all studies between 1995 and 2012) demonstrated their usefulness in decreasing mortality in cardiac surgical patients, but they did reduce morbidity (postoperative complications) and hospital length of stay [5, 103, 104]. There are some potential causes which could explain the fact that despite the application of modern flow-related GDT protocols the results in cardiac surgery are poor related to mortality and in contrast with the data found in non-cardiac surgery. The first reason to consider is the relatively low mortality in cardiac surgery (1-5%) [105] in comparison with the suggested group of patients that could benefit the most from GDT protocols in terms of mortality: namely those with a predicted mortality around 20% [103-105]. Another explanation could be the heterogeneity of the multiple targets proposed in various GDT protocols.

Conclusions

Currently, various algorithms based on APW analysis have been elaborated and the measurements of SV and continuous CO based on this technology have become part of our daily practice both in the operating room and the ICU. Probably, the APW analyzers are the most promising hemodynamic monitoring devices because they are easy to use and provide parameters able to be included in GDT strategies and above all minimally invasive.

The calibrated APW methods are considered to be more reliable in measuring the SV or CO and in tracking the changes in CO.

Nowadays, among the APW devices only PiCCO and Flotrac/Vigileo were used in GDT-RCT in cardiac surgical patients. Despite the promising premises, the APW monitoring devices did not demonstrate that they played a role in decreasing mortality in that population but only decreased the ventilation time and the ICU and the hospital length of stay.

Conflict of interest

Nothing to declare

Disclosure

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Dispozitivele de monitorizare hemodinamică a undei de puls: progrese recente şi locul în terapia ţintită a pacientului cardiac chirurgical

Rezumat

În ultima decadă posibilităţile de monitorizare hemodinamică au evoluat enorm şi s-au rafinat tehnic urmând noul tip de abordare clinică prin care s-a renunţat la evaluarea statică în favoarea conceptului dinamic de definire a statusului hemodinamic. Astfel, în practica clinică au intrat tot mai multe metode de monitorizare hemodinamică bazate pe analiza curbei presiunii arteriale (ACPA), unele dintre acestea necesitând o calibrare iniţială, altele nu, multe dintre aceste metode fiind minim-invazive sau chiar non-invazive. În această lucrare am explicat principiile de funcţionare ale acestor noi tehnici de monitorizare şi am analizat în mod sistematic avantajele precum şi limitele acestora, cu un accent special pe fiabilitatea noilor metode în măsurarea unor parametri uzuali precum volumul bătaia şi debitul cardiac, dar şi în măsurarea unor parametri dinamici ai predicţiei răspunsului debitului cardiac la administrarea de volum. De asemenea, am analizat sistematic şi rolul noilor metode ACPA în strategiile de optimizare hemodinamică adresate pacientului de chirurgie cardiacă. În conformitate cu datele din cele trei studii randomizate de optimizare perioperatorie publicate până în prezent şi în care s-au utilizat metode de monitorizare bazate pe tehnologia APCA (2 studii cu PiCCO şi unul cu FloTrac/Vigileo), utilizarea acestei tehnologii în protocoalele respective nu a diminuat mortalitatea pacienţilor de chirurgie cardiacă, ci a produs doar o scădere a perioadei de ventilaţie mecanică postoperatorie, precum şi a duratei şederii în terapie intensivă şi în spital.

Cuvinte cheie: monitorizare hemodinamică minim invazivă şi non invazivă, tehnologie bazată pe analiza curbei presiunii arteriale, optimizare hemodinamică perioperatorie prin protocoale ţintite, chirurgie cardiovasculară