EMERGING TECHNOLOGY REVIEW

Gerard R. Manecke, Jr, MD
Section Editor

Transcardiopulmonary Thermodilution-Calibrated Arterial Waveform Analysis: A Primer for Anesthesiologists and Intensivists

Nicola S. Laight, MBChB, and Andrew I. Levin, MBChB, DA, MMed (Anes), FCA, PhD

USE OF THE pulmonary artery catheter, the current clinical gold standard for cardiac output (CO) measurement,[1–4] is declining rapidly particularly outside cardiothoracic surgery.[5,6] One frequently quoted reason for this decline – that the device is too invasive – has coincided with the development of "less invasive" CO measurement techniques for monitoring of early goal-directed hemodynamic therapy (EGDT).[3,7–9] One of these less invasive techniques is transpulmonary (or transcardiopulmonary) thermodilution-calibrated arterial waveform analysis ($CO_{TPTD\text{-}AWA}$).[10–13] $CO_{TPTD\text{-}AWA}$ devices contain 2 separate technologies: (1) transcardiopulmonary thermodilution (CO_{TPTD}) for calibration, which is linked to (2) mathematical analysis of the arterial pressure-time waveform for continuous CO estimation (CO_{AWA}) (Fig 1).

The numerous publications describing use of this technology indicate that it is gaining rapid acceptance as a physiologic monitor[9,13–37] and as a reference standard in research.[38–41] Its scientific applications have included monitoring of lung water and fluid therapy in acute lung injury[36,42–62]; physiologic monitoring in adult[18,19,63–67] and pediatric[68–71] cardiac surgery and hepatic surgery[72–75]; and monitoring of critically ill pediatric[76–81] and adult patients with burns,[82–84] sepsis,[85–88] and intracranial pathology.[89–93]

$CO_{TPTD\text{-}AWA}$ and the derived additional hemodynamic parameters employ elusive processes to derive CO.[8,10–13,94] To appreciate the possible uses, advantages, limitations, and potential inaccuracies of research incorporating this emerging technology, the practitioner requires an understanding of the principles underlying $CO_{TPTD\text{-}AWA}$.[95]

The principles underlying CO_{TPTD} are similar to CO estimation using a thermodilution pulmonary artery catheter (CO_{PAC}) (Fig 2).[10,11,96,97] In both techniques, a bolus of saline colder than body temperature is administered via a central venous catheter. A downstream thermistor-tipped catheter, located in the pulmonary artery with CO_{PAC} and in close proximity to the aorta with CO_{TPTD}, detects the consequent temperature change.

Performing CO_{TPTD} requires insertion of a central venous catheter and a thermistor-tipped arterial catheter; the latter is inserted close to or in the aorta. Iced saline boluses (usually 10-20 mL in adults) are injected via the central venous catheter. The consequent arterial temperature decrease is detected by the arterial thermistor. The "thermodilution" curve is used to estimate CO. Typically, 3 thermodilution CO determinations are averaged to provide a reference CO estimation. A separate but linked system mathematically uses this reference CO and mathematical analysis of the arterial pressure-time waveform to calculate CO continuously (Fig 1).

$CO_{TPTD\text{-}AWA}$ frequently is called PiCCO (pulse index continuous cardiac output), which refers to specific commercially available technology (PULSION Medical Systems SE, Feldkirchen, Germany) that is available either as a stand-alone or a modular device; the latter is compatible with physiologic monitors from various manufacturers (Philips, Andover, MA; GE Healthcare, Chalfont St. Giles, United Kingdom; Dräger-werk AG, Lübeck, Germany; Shenzhen Mindray Bio-Medical Electronics, Shenzen, China; Maquet, Rastatt, Germany). PiCCO technology has been available for more than a decade, and similar technology (VolumeView and EV1000; Edwards Lifesciences, Irvine, CA) has become available more recently for clinical use. For the sake of impartiality, the authors refer to the techniques as $CO_{TPTD\text{-}AWA}$ wherever possible.

ARTERIAL WAVEFORM ANALYSIS: COMPUTING FLOW FROM PRESSURE

More than 100 years ago, physiologists Frank and Erlanger independently stated that pulse pressure was related to stroke volume.[98] Frank developed the Windkessel model of the circulation with the explicit purpose of deriving blood flow from arterial pressure; this method is still the basis of arterial CO_{AWA}.[94] However, the long history attests to the difficulties encountered while translating the physiologist's principles into the recently developed, accurate measurement of CO.[99,100]

The original pulse contour method attempted to derive stroke volume by dividing the area under the systolic aortic pressure-time relationship by (a pressure- and heart rate-corrected value of) aortic impedance.[21,100–105] This method contained a major flaw in that aortic compliance was assumed to be a constant and independent of aortic pressure.[94,106] Wesseling's group identified this flaw. They studied 45 excised

From the Department of Anesthesiology and Critical Care, University of Stellenbosch, Tygerberg Hospital, Cape Town, South Africa.

Address reprint requests to Andrew Levin, MBChB, DA, MMed (Anes), FCA, PhD, Department of Anesthesiology and Critical Care, University of Stellenbosch and Tygerberg Hospital, Room 2044, Clinical Building, Cape Town, Western Cape 7505, South Africa. E-mail: ail@sun.ac.za

1053-0770/2601-0001$36.00/0
http://dx.doi.org/10.1053/j.jvca.2015.03.013
Key words: cardiac output, transcardiopulmonary thermodilution, hemodynamic monitoring, arterial waveform analysis, Modelflow technique, PiCCO, Edwards EV-1000

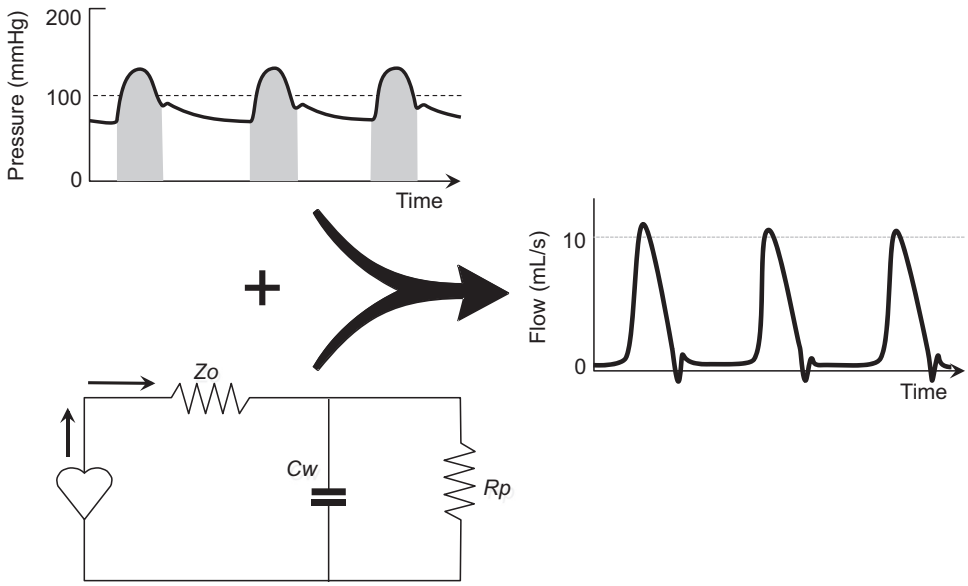

Fig 1. The principles underlying the Modelflow method. The arterial pressure versus time waveform is transformed into a flow versus time relationship with input from the Windkessel model of the circulation.

cadaver thoracic aortas and derived a mathematical formula that accurately described the relationship among aortic pressure, aortic diameter, and aortic compliance.[94,107–109] This formula permitted the development of the Modelflow technique,[94] the technology underpinning the PiCCO and EV1000 devices and certain other present-day CO_{AWA} techniques.[105] The Modelflow technique is more accurate than the pulse contour CO_{AWA} method, the accuracy (mean ± SD) of the 2 techniques being 2 ± 8% (Modelflow) and 6 ± 12% (pulse contour CO_{AWA}).

Understanding the complexity of the Modelflow CO_{AWA} method allows appreciation of the associated potential pitfalls and solutions. The Modelflow CO_{AWA} technique comprises 2 steps (Fig 1). The first step involves transforming the arterial

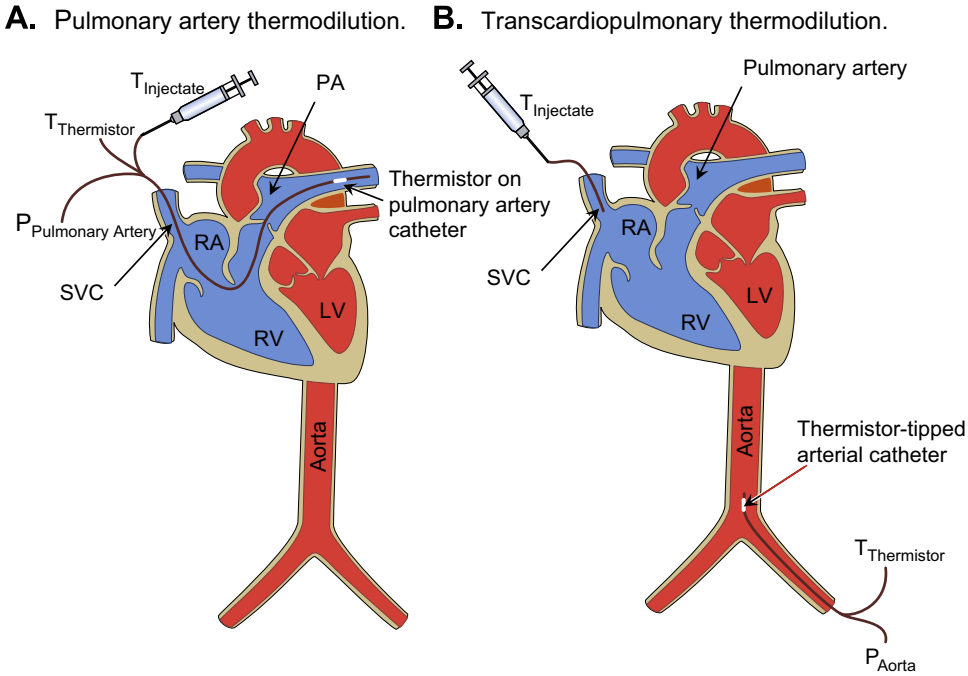

Fig 2. Comparison of pulmonary artery (A) and transcardiopulmonary (B) thermodilution techniques. $T_{INJECTATE}$ and $T_{THERMISTOR}$ represent the measurement of injectate temperature at the sites of injection and at the pulmonary and aortic thermistors, respectively; $P_{PULMONARY\ ARTERY}$ and P_{AORTA} represent pulmonary artery and aortic pressures, respectively. LV, left ventricle; RA, right atrium; RV, right ventricle; SVC, superior vena cava.

pressure-time waveform into a flow-time waveform; the second step involves integration of the area under the derived flow-time waveform to derive stroke volume.[21,100,110–112]

The arterial pressure-time information is transformed into a flow-time relationship using the Windkessel equation (Equation 1).[94] This step essentially represents the quotient of instantaneous arterial pressure and aortic input impedance.[94,111,113]

$$i_t = \frac{P_t}{R_{Total}} + C_w \frac{dPt}{dt} \quad (1)$$

where i_t is aortic flow, P_t is systolic aortic blood pressure, dPt/dt is the rate of change in pressure, R_{Total} is total peripheral resistance, and C_w is arterial compliance.

The Windkessel equation incorporates multiple parameters representing opposition to flow, including the following:[105,110,111,114,115]

1. Aortic characteristic impedance (Z_0), defined as the opposition to pulsatile left ventricular ejection presented by the aorta, a relatively small force comprising 5% to 7% of systemic vascular resistance (SVR);
2. Arterial compliance (Cw), the elastic forces opposing left ventricular ejection;
3. Systemic peripheral resistance (Rp), the Poiseuille resistance of all vascular beds at constant laminar flows; and
4. Total peripheral resistance (R_{TOTAL}), the sum of aortic characteristic impedance (Z_0) and systemic peripheral resistance (Rp).

It is straightforward to acquire the pressure-related parameters from the aortic pressure trace; however, each impedance parameter needs to be determined to compute flow from pressure successfully using Equation 1. Despite aortic characteristic impedance being an elusive parameter, Langewouters et al[107] successfully described its derivation from a complex relationship among blood density, aortic compliance, and aortic area (Equation 2).

$$Zo = \sqrt{\frac{\rho}{ACwl}} \quad (2)$$

where A is aortic area, Cwl is aortic compliance per unit length of the aorta, and ρ is blood density.

The mathematical relationship established by Wesseling's group reveals aortic compliance to be a nonlinear, pressure-dependent parameter that decreases rapidly with increases in pressure.[94,107,108] Age and gender significantly influence aortic compliance; weight and height affect this parameter only slightly. A decrease in aortic compliance related to atherosclerosis possibly would compromise the accuracy of the Windkessel mathematical relationship to transform pressure to flow; such an expected decrease in compliance is negated by the accompanying, consistently larger aortic diameter accompanying atherosclerosis.[107]

Newer, more accurate $PiCCO_2$ software[105,115] uses a different method of calculating aortic compliance. The principle is that the time constant (τ) of the exponential pressure decline after the dicrotic notch can be computed from the product of aortic compliance and SVR.[116] The time constant is computed easily from the rate of decline (dPt/dt) in diastolic pressure, whereas SVR is calculated using the quotient of mean arterial pressure and the reference method of determining CO (see later). This refinement of calculating compliance continuously apparently improves CO_{AWA} performance and reduces the need for recalibration, particularly when hemodynamics are rapidly changing.[117] Despite this refinement, the method of Langewouters et al of deriving aortic diameter that incorporates a 30% SD (see later) still is required.

The Windkessel equation (Equation 1) requires SVR data to convert pressure-time to flow data. Modelflow CO_{AWA} techniques calculate SVR, assume it, or both. Calibrated Modelflow $CO_{TPTD-AWA}$ techniques initially calculate SVR from the quotient of mean arterial pressure and mean flow (CO), the latter obtained from the initial CO_{TPTD}. However, uncalibrated Modelflow CO_{AWA} techniques assume an initial "reasonable value" of SVR based on patient demographics.[94]

After initial calculation or assumption of SVR, calibrated and uncalibrated Modelflow CO_{AWA} techniques assume that SVR changes relatively slowly, with a time constant approximating 10 seconds.[94,101] This assumption sanctions a technique whereby SVR is updated continuously. This technique uses the SVR calculated initially in the Windkessel CO_{AWA} analysis of the first beat. During the Windkessel CO_{AWA} analysis of the second beat, the pressure-flow relationship (SVR) data of the first beat are used, and so forth.[101] This iterative method supposedly represents a "self-correcting" or "self-adapting" system in which SVR converges to the correct value within a few heartbeats even without initial accurate reference measurements of flow and pressure.[101,118]

SVR can change very rapidly in current anesthesia, surgery, and intensive care practice. Assuming that SVR is constant and that the value from the previous beat can be used safely in the next beat has the potential to become (progressively more) inaccurate.[119–122] The solution is simply to recalibrate using CO_{TPTD}. This recalibration permits calculation of an updated, accurate SVR. With uncalibrated Modelflow techniques, the initial "reasonable value" is subject to major assumptions, particularly in ill patients.

For computing CO continuously, aortic pressure typically is sampled at 100 Hz, and a flow-time relationship is created using instantaneous aortic characteristic impedance and compliance values (Figure 1).[101,105] After derivation of the flow-time relationship, the second essential step in CO_{AWA} is to calculate stroke volume using mathematical integration of the area under the systolic part of the flow-time relationship. CO is then calculated as the product of stroke volume and heart rate (Equation 3).[21,100,110]

$$Cardiac\ output = [calibration\ factor] \times [heart\ rate] \times \int \left(\frac{P(t)}{SVR + Cw} + \frac{dP}{dt}\right) dt \quad (3)$$

The details of CO_{AWA} computation differ between the VolumeView/EV1000 and the newer $PiCCO_2$ devices. The VolumeView/EV1000 device relies on both of the conventional processes described earlier but also incorporates "advanced" wave-shape parameters to calculate CO_{AWA}.[123,124] These advanced parameters analyze waveform skewness and kurtosis.[13]

Skewness is a mathematical measure of arterial waveform asymmetry used to indicate changes in vascular resistance.[124] Kurtosis mathematically describes the shape (how peaked or flat) of a sample distribution compared with a normal distribution.[124] Arterial waveforms with high kurtosis peak rapidly and have heavy tails and are typical of higher vascular resistance states. In uncalibrated CO_{AWA}, it is used to compensate for the differences in compliance between arterial measurement sites. The exact relationship between the conventional and "advanced" parameters is corporate, guarded information.[13,124]

VolumeView/EV1000 and $PiCCO_2$ technologies have similar accuracy; 1 study suggested that VolumeView/EV1000 has slightly (20%) greater precision than $PiCCO_2$.[13] This greater precision is attributed to the incorporation of advanced waveform analysis, which compensates for difficulties in automatic identification of the dicrotic notch.[13] Further detail regarding "advanced" techniques is beyond the scope of this article; the interested reader is referred to Benjelid et al[12] and Pratt et al.[124]

DETERMINING A CALIBRATION FACTOR USING INTERMITTENT CO_{TPTD}

Maximizing accuracy for pulse contour and Modelflow CO_{AWA} always has necessitated initial calibration using an independent method of estimating CO.[101,117] CO_{PAC} was used previously with pulse contour analysis techniques[117]; at the present time, lithium dilution and transpulmonary thermodilution more commonly are used to estimate initial reference CO. Knowledge of a reference CO allows computation of a calibration factor specific to a patient and hemodynamic state (Equation 3) for CO_{AWA}.[11,12,96,104,123,125]

A reference CO and a calibration factor are needed because the aortic pressure-compliance, pressure-diameter, and pressure-impedance relationships described by Wesseling and Langewouters are "population averages", with standard deviations and 95% confidence intervals approximating 20% and 30%, respectively.[96,100,101,110,126] Wesseling et al stated, "Given the 20% scatter …, Modelflow cannot be computed with an accuracy better than this percentage."[94] It is not surprising that compared with CO_{PAC} or calibrated CO_{AWA}, uncalibrated Modelflow and other CO_{AWA} devices still have significant issues related to accuracy.[13,19,28,29,32,127–144]

The principles underlying CO_{TCTD} are based on Fick's principle and use the modified Stewart-Hamilton equation.[10,11,96,97] A thermistor, similar to that located near the tip of a thermodilution pulmonary artery catheter used to determine CO_{PAC}, is built into a customized arterial catheter to register accurately blood temperature changes after intravenous injection of an iced saline bolus (Fig 2). For accurate CO_{TPTD}, this thermistor needs to be in or very close to the aorta. The resultant plot of temperature versus time ("thermodilution" curve) (Fig 3) is input into the computer, and CO is computed

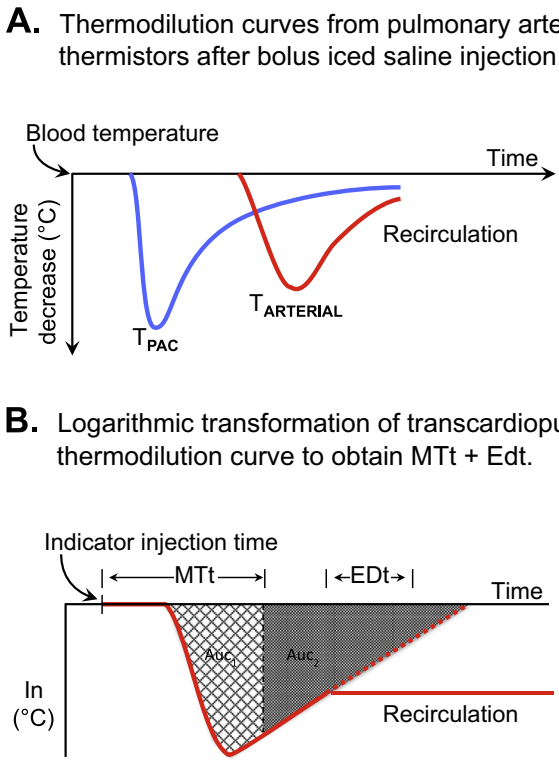

Fig 3. (A) Thermodilution curves from pulmonary artery and arterial-aortic thermistors after bolus iced saline injection. (B) Logarithmic transformation of a transcardiopulmonary arterial thermodilution curve to obtain MTt (mean transit time) and exponential decay time. Mean transit time is when the area under the thermodilution curve (AUC) is divided into two equal areas (AUC_1 and AUC_2). Exponential decay time is the initial rate of decay of the thermodilution curve. Assuming a monoexponential decay, the rate of decay can be measured at any time point after the peak. It usually is measured as the slope between two set-points in the thermodilution curve (eg, 80% and 40%). The monitor observes central venous pressure: The precise time of iced saline bolus administration is determined by the rapid supraphysiologic increase in pressure.

using the modified Stewart-Hamilton equation. Typically, 2 to 5 thermodilution CO determinations randomly dispersed throughout the respiratory cycle are averaged and used to calibrate the continuous CO_{AWA} device, albeit adequate precision can be obtained with only 2 determinations.[145]

Following simultaneous indicator injection, comparison of pulmonary artery- and transcardiopulmonary-derived thermodilution curves (Fig 3) revealed the latter to have a delayed, smaller trough temperature decrease and a slower return to baseline. These differences between techniques have disparate effects on accuracy. On the one hand, CO_{TCTD} slightly but consistently underestimates CO_{PAC} by 3%.[116,146–149] This discrepancy is due to greater dissipation of indicator (heat) to adjacent tissues along the longer pathway[11,97,104,150] and the greater decrease in cardiac temperature, which deleteriously affect heart rate and cardiac performance.[32,151–154] On the other hand, compared with CO_{PAC}, the greater transcardiopulmonary mixing time minimizes CO_{TCTD} errors provoked by respiratory-induced temperature changes.[32,96,125] Greater CO_{TCTD} accuracy can be achieved through using ice-cold ($\leq 8^{\circ}C$), larger volume (20 mL) boluses of saline indicator. Although it has been suggested that room-temperature injectate may provide acceptable results,[155] this causes CO to be overestimated by 21.9%.[156] The effects of a bigger, colder indicator bolus include increased magnitude of downstream temperature changes, accentuation of the thermodilution curve downslope, and maximization of the area under the curve.[150]

CLINICAL CONSIDERATIONS WHEN USING $CO_{TPTD-AWA}$

Hemodynamic monitoring aims to manipulate oxygen delivery and consumption so that patient outcomes are improved and healthcare resource consumption is reduced.[3,157–163] These goals have been achieved in high-risk surgical patients and critically ill trauma or septic patients using the Enhanced Recovery After Surgery (ERAS) programs, perioperative fluid optimization, and EGDT programs.[164–171] The hemodynamic goals of these programs likely overlap.[157,163,167,172–175] Despite controversy surrounding the pulmonary artery catheter, EGDT outcome improvements appear to be independent of the specific CO measurement technology.[157,172,173,176–178] Because $CO_{TPTD-AWA}$ measures CO accurately[117,179] and continuously, it is reasonable to hypothesize that its use in EGDT may improve outcomes. Apart from the studies by Goepfert et al[180,181] demonstrating reductions in inotrope usage, length of stay, and complications after cardiac surgery, a dearth of high-quality evidence exists regarding the benefits of $CO_{TPTD-AWA}$-guided EGDT.[9,21,182]

The major clinical and practical considerations when using $CO_{TPTD-AWA}$ are as follows: ensuring accurate arterial pressure waveform reproduction, ensuring that the arterial thermistor is within or in proximity to the aorta for accurate CO_{TPTD}, consideration of conditions precluding use of this technology, and knowing when recalibration is needed.

The Modelflow CO_{AWA} technique requires faithful reproduction of the aortic pressure waveform. Damped arterial catheter systems (kinks, clots, air bubbles, compliant excessive length tubing) with inadequate frequency response contribute significantly to CO_{AWA} errors.[105] Although peripheral arterial pressure can be used to calculate CO_{AWA},[116,183] arterial wave reflection causes the shape of the arterial and aortic waveforms to differ.[101,184] Some devices can use a transformed peripheral waveform, but the algorithm used to transform a peripheral into an aortic pressure waveform has not been made public.[183] Mostly, physicians use 4F or 5F, 15- to 20-cm-long femoral catheters to access the aorta.[11,185] For nonfemoral (radial, brachial, or axillary) aortic access, PULSION currently offers catheters equipped with thermistors of various (8-50 cm) lengths.[186,187] These long arterial catheters deliver reliable CO measurements,[187–189] although progressively greater measurement errors occur with more distal arterial locations of the catheter tip.[188] Long upper limb catheters risk stroke either from ascending aortic plaque dislodgment or from catheter flushing with retrograde embolization of clot or air. Limb ischemia has occurred, albeit infrequently, after placement of long upper limb[190–193] and femoral arterial catheters.[194] In patients undergoing vascular surgery, femoral arterial-aortic cannulation frequently is inadvisable because of lower limb vascular disease, iliac or femoral surgery and grafting, or anticipated aortic clamping.[105] This technology can and has been used successfully with femoral arterial catheters in children undergoing major surgery.[69,75–79,81]

The use of Modelflow CO_{AWA} is precluded by aortic aneurysms,[11] aortic clamping, significant aortic regurgitation, induced hypothermia,[195] artificial hearts, ventricular assist devices,[124] arrhythmias,[105] and intra-aortic balloon counterpulsation. CO_{TPTD} appears to be accurate in the presence of intra-aortic balloon counterpulsation.[196]

Loss of indicator can occur with regurgitant right-sided cardiac lesions and right-to-left cardiac shunts; the latter are typified by a biphasic 2-hump (camel) thermodilution curve.[197] CO and extravascular lung water (but not global end-diastolic volume index) data are interchangeable when the indicator is administered via either a superior vena cava or femoral venous catheter.[198,199] Ipsilateral femoral vein and artery placement of central venous and arterial catheters should be avoided to prevent "crosstalk."[200] "Crosstalk" refers to temperature contamination of the arterial thermistor by ipsilateral femoral vein cold saline injection; this scenario also is characterized by a biphasic thermodilution curve.[198–202]

A significant, unresolved issue occurs when Modelflow CO_{AWA} warrants recalibration. Authorities recommended recalibration every 6 to 8 hours under stable conditions.[11] Recommendations regarding the recalibration interval range from 1[120] to 44 hours.[105,117,203,204] This discrepancy is explained by the need for recalibration not being time related, but CO_{AWA} becoming inaccurate following rapid hemodynamic changes, particularly following changes in SVR.[65,106,121,127,204] After initial calibration, mild changes in SVR did not affect Modelflow CO_{AWA} accuracy;[205] however, CO_{AWA} errors of up to 40% occurred if SVR changed by $>15\%$.[122,204,206,207] Modelflow CO_{AWA} accuracy is critically dependent on vascular tone, and the technique assumes that vascular resistance is relatively constant.[208] Suggestions that clinicians recalibrate after weaning from cardiopulmonary bypass,[209,210] acute hemorrhage or rapid fluid infusion, inotrope-vasopressor administration,[106,207] patient repositioning, aortic clamping and unclamping, and onset of intra-abdominal hypertension and sepsis[211] are logical.[212–214] An important advantage of the CO_{TPTD} calibration

method is that it may be repeated as needed because the iced saline indicator is not toxic and does not risk accumulation. Recalibration can be cumbersome, time-consuming, and inconvenient at times of hemodynamic instability—this being the exact situation in which robustness and knowledge of CO are likely to be of most use.[66,120,132,142,143] Indicators of exactly when Modelflow CO_{AWA} requires recalibration remain a subject for research.[204,207,215]

CO_{TPTD} assumes a constant arterial temperature during the measurement period. Deviations from "baseline" temperature that are not due to the iced saline bolus constitute "thermal noise", with deleterious effects on CO_{TPTD} precision and accuracy.[216,217] The effect of hypothermia on CO_{TPTD} accuracy has not been well studied.[216,217]

INDICATORS OF PRELOAD OBTAINED FROM CO_{TPTD} AND AWA_{CO} MONITORS

CO_{TPTD} can provide a series of indicators of preload, including intrathoracic thermal volume (ITTV), pulmonary thermal volume (PTV), global end-diastolic volume (GEDV), and intrathoracic blood volume (ITBV) (Fig 4).[218] Stroke volume and pulse-pressure variation derived from the arterial pressure-time waveform are not unique to this technique and have been reviewed elsewhere.[219]

The first determination in Fig 4, ITTV, the total volume of blood contained in both cardiac chambers and the pulmonary vasculature, is the volume of distribution between injection and measurement sites ("needle-to-needle" volume). ITBV was measured formerly using a double-tracer method relying on the Fick principle. This double-tracer method was composed of intravenous bolus injection of iced dextrose water mixed with indocyanine green. Indocyanine green binds to plasma proteins, stays intravascularly, and provides an indication of ITBV. The double-indicator and CO_{TPTD} techniques differ. When the thermal signal of the latter contacts the huge surface area of the pulmonary circulation, heat disperses to intravascular and extravascular spaces within the lungs. CO_{TPTD} calculates ITTV[96,97,104,150,212,220]; this value exceeds ITBV measured using the double-indicator technique. Nonetheless, Godje et al[220] established that the thermal indicator technique is sufficiently accurate to supplant the double-indicator method.

The method of ITTV measurement involves use of the product of CO and mean transit time, the latter being the time taken for half the indicator solution to pass the arterial detection point (Fig 3B). The VolumeView/EV1000 modification uses the maximum upslope and downslope of the thermodilution washout curves; this provides volumes comparable to the PiCCO monitor, but has the putative advantage of avoiding problems with identifying recirculation.[221]

After estimating ITTV, PTV can be calculated (Fig 4). While using indocyanine green to estimate CO, Hamilton observed that the dye washout rate was determined not only by CO but also by the sizes of the "mixing chambers" into which the indicator had been injected.[222] Newman et al[222] refined this hypothesis as follows: If the cardiac chambers and vessels are considered as a series of mixing compartments into which indicator is added, the indicator washout rate should be proportional to the size of the largest mixing chamber.[69] These authors demonstrated mathematically and experimentally that

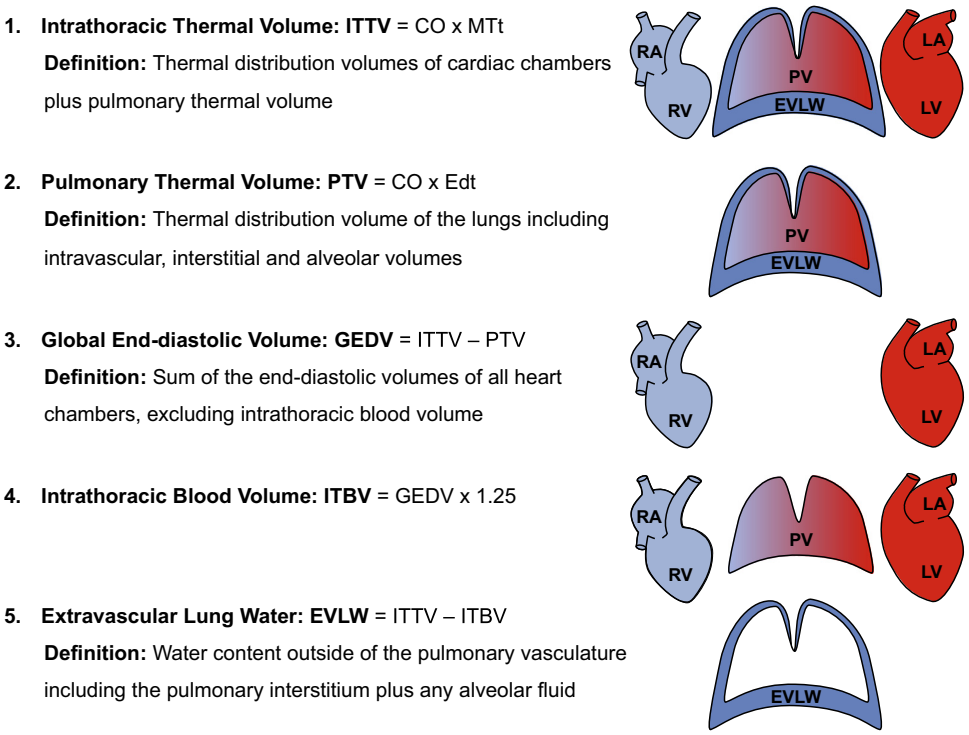

Fig 4. The principles and formulas underlying calculation of intrathoracic volumes and extravascular lung water. LA, left atrium; LV, left ventricle; PV, pulmonary vasculature; RA, right atrium; RV, right ventricle.

the volume of this largest chamber was the quotient of CO and the slope of the semilogarithmic indicator concentration versus time washout curve. The pulmonary (thermal) blood volume can be estimated from the product of the initial washout rate of the CO_{TPTD} curve termed the "exponential decay time" and CO (Fig 3).[69,222] A semilogarithmic transformation of the CO_{TPTD} curve is performed to facilitate accurate measurements of exponential decay time and other parameters.[11,96,202,223] The theory by Newman et al[222] is based on the assumptions that injection of indicator is instantaneous, indicator and blood mix completely and immediately, pulmonary blood volume is constant and does not change with ventilation, recirculation does not occur, and flow is constant.

GEDV, the end-diastolic volume of blood in the cardiac chambers (Fig 4), is the difference between ITTV and PTV. Sakka et al[224] described intrathoracic blood volumes to consistently be 1.25 times greater than GEDV.

GEDV and ITBV have been compared with central venous pressure and pulmonary capillary wedge pressure as measures of preload. Although good relationships between these volumetric indices with stroke volume and prediction of fluid responsiveness have been demonstrated,[24,225–228] other research indicates significant interindividual variation,[229] that they are not superior[230] or as accurate as dynamic measures of preload,[231] and that their application may be limited to situations in which arrhythmias would preclude the use of pulse-pressure variation or stroke-volume variation.[96]

INDICATORS OF EXTRAVASCULAR LUNG WATER OBTAINED FROM CO_{TPTD}

Extravascular lung water (EVLW) effectively represents the volume of distribution of the cold indicator in the perfused areas of the lungs.[150,232] It is estimated from the difference between ITTV and ITBV (Fig 4); these measurements compare favorably with measurements derived from gravimetry, the gold standard EVLW measurement technique.[202,233–239] The normal range of EVLW is 3 to 7 mL/kg, but EVLW typically is >10 mL/kg in pulmonary edema.[233,240–242] EVLW progressively increases with the severity of acute lung injury.[240–244] It has been proposed as a diagnostic,[240,243–248] prognostic,[245,249–251] and therapeutic guide[233,252] to fluid administration in acute lung injury and other conditions.[228]

Despite its promise, the single-indicator (thermal) dilution method of measuring EVLW has not yet been adopted widely or accepted for clinical use.[236] It also has several potential problems[96,233,235,236,253]; reviews by Effros et al[254] and Brown et al[236] indicated that the assumptions used in EVLW measurements may not always be valid. The reliability and sensitivity to detect smaller changes of EVLW have been questioned[233,253–256] because EVLW has been found within normal limits in 35% of patients with acute lung injury.[200] More specifically, obstruction of pulmonary vessels prevents conduction of thermal indicator to the extravascular spaces causing underestimation of EVLW. This issue occurs only if obstruction arises in vessels >500 μm in diameter; micro-obstruction as found in acute lung injury does not pose a problem. The effect of positive end-expiratory pressure depends on whether pulmonary vascular obstruction or alveolar recruitment results, causing underestimation and overestimation of EVLW, respectively. Lung resection decreases pulmonary blood volume, distorting the relationship between GEDV and EVLW, causing underestimation of the latter.[233] The contention that ITBV and CO are mathematically coupled has been repudiated.[203,223,224,232]

INDICATORS OF CARDIAC PERFORMANCE OBTAINED FROM CO_{TPTD}

CO_{TPTD} provides 2 indices of performance: cardiac function index, the quotient of CO and GEDV (units = $minute^{-1}$), and global ejection fraction, the quotient of 4 times stroke volume and GEDV.[179,257,258] These indices correlate with ($r^2 = 0.27$-0.76) and track left ventricular systolic function during various clinical situations (eg, sepsis, acute myocardial infarction, acute cardiac failure).[88,128,259] Cardiac function index <3.7 to 6.8 $minute^{-1}$ and global ejection fraction $<28\%$ predict left ventricular ejection fraction $<35\%$ to 40%, with sensitivity and specificity values between 86% and 81% and 63% and 88%, respectively.[88,128,257,259]

Cardiac function index and global ejection fraction represent global left and right ventricular performance.[128,257] These parameters do not represent left ventricular function in the presence of predominant right ventricular dilation[128,257]; they cannot replace echocardiographic assessment and discrimination of left and right ventricular dysfunction.[128,257,260,261]

FUTURE DEVELOPMENTS

The most pressing issue is validation of whether $CO_{TPTD-AWA}$-guided EGDT and therapy guided by derived volumetric and cardiac function parameters will enhance recovery after surgery and improve intensive care outcomes.[9,59] Whether dissimilar cardiac output monitoring technologies are interchangeable also needs to be addressed.[9,137,142,143] Future technologic developments may include a "transfer function" to ensure satisfactory accuracy when using peripheral arterial catheterization.[100,183] Instead of standalone monitors, manufacturers will likely license incorporation of this technology into a wider variety of multiparameter physiologic monitors. Such integrated monitoring platforms would permit an assortment of allied CO measurement techniques, such as intermittent bolus CO_{PAC} and CO_{TPTD}, continuous thermoaddition CO_{PAC}, and calibrated or uncalibrated CO_{AWA}; in the future, finger CO_{AWA}[14,262] and radial artery applanation tonometry may become options in the same monitor.[28,37] Such versatility would allow customization of EGDT appropriate to the clinical scenario.[15]

CONCLUSIONS

$CO_{TCTD-AWA}$ technology is a useful hemodynamic tool. However, as with any monitoring device, an understanding of the technology as well as an appreciation of its limitations are needed. Interpretation of the data obtained from CO measurement technology within the clinical context will ensure its safe and appropriate use in guiding patient management.

REFERENCES

1. Richard C, Monnet X, Teboul JL: Pulmonary artery catheter monitoring in 2011. Curr Opin Crit Care 17:296-302, 2011
2. Pugsley J, Lerner AB: Cardiac output monitoring: Is there a gold standard and how do the newer technologies compare? Semin Cardiothorac Vasc Anesth 14:274-282, 2010
3. Vincent JL: The pulmonary artery catheter. J Clin Monit Comput 26:341-345, 2012
4. Rajaram SS, Desai NK, Kalra A, et al: Pulmonary artery catheters for adult patients in intensive care. Cochrane Database Syst Rev 2: CD003408, 2013
5. Wiener RS, Welch HG: Trends in the use of the pulmonary artery catheter in the United States, 1993-2004. JAMA 298:423-429, 2007
6. Rubenfeld GD, McNamara-Aslin E, Rubinson L: The pulmonary artery catheter, 1967-2007: Rest in peace? JAMA 298:458-461, 2007
7. Robin E, Costecalde M, Lebuffe G, et al: Clinical relevance of data from the pulmonary artery catheter. Crit Care 10(Suppl 3):S3, 2006
8. Marik PE: Noninvasive cardiac output monitors: A state-of the-art review. J Cardiothorac Vasc Anesth 27:121-134, 2013
9. Thiele RH, Bartels K, Gan TJ: Inter-device differences in monitoring for goal-directed fluid therapy. Can J Anaesth 62: 169-181, 2015
10. Lee AJ, Cohn JH, Ranasinghe JS: Cardiac output assessed by invasive and minimally invasive techniques. Anesthesiol Res Pract 2011:475151, 2011
11. Litton E, Morgan M: The PiCCO monitor: A review. Anaesth Intensive Care 40:393-409, 2012
12. Bendjelid K, Giraud R, Siegenthaler N, et al: Validation of a new transpulmonary thermodilution system to assess global end-diastolic volume and extravascular lung water. Crit Care 14:R209, 2010
13. Bendjelid K, Marx G, Kiefer N, et al: Performance of a new pulse contour method for continuous cardiac output monitoring: Validation in critically ill patients. Br J Anaesth 111:573-579, 2013
14. Ameloot K, Van De Vijver K, Broch O, et al: Nexfin non-invasive continuous hemodynamic monitoring: Validation against continuous pulse contour and intermittent transpulmonary thermodilution derived cardiac output in critically ill patients. ScientificWorld-Journal 2013:519080, 2013
15. Monnet X, Picard F, Lidzborski E, et al: The estimation of cardiac output by the Nexfin device is of poor reliability for tracking the effects of a fluid challenge. Crit Care 16:R212, 2012
16. Horster S, Stemmler HJ, Sparrer J, et al: Mechanical ventilation with positive end-expiratory pressure in critically ill patients: Comparison of CW-Doppler ultrasound cardiac output monitoring (USCOM) and thermodilution (PiCCO). Acta Cardiol 67:177-185, 2012
17. Horster S, Stemmler HJ, Strecker N, et al: Cardiac output measurements in septic patients: Comparing the accuracy of USCOM to PiCCO. Crit Care Res Pract 2012:270631, 2012
18. Broch O, Renner J, Gruenewald M, et al: Variation of left ventricular outflow tract velocity and global end-diastolic volume index reliably predict fluid responsiveness in cardiac surgery patients. J Crit Care 27:325.e327-313, 2012
19. Broch O, Renner J, Gruenewald M, et al: A comparison of the Nexfin and transcardiopulmonary thermodilution to estimate cardiac output during coronary artery surgery. Anaesthesia 67:377-383, 2012
20. Galstyan G, Bychinin M, Alexanyan M, et al: Comparison of cardiac output and blood volumes in intrathoracic compartments measured by ultrasound dilution and transpulmonary thermodilution methods. Intensive Care Med 36:2140-2144, 2010
21. Montenij LJ, de Waal EE, Buhre WF: Arterial waveform analysis in anesthesia and critical care. Curr Opin Anaesthesiol 24: 651-656, 2011
22. Laleg-Kirati TM, Medigue C, Papelier Y, et al: Validation of a semi-classical signal analysis method for stroke volume variation assessment: A comparison with the PiCCO technique. Ann Biomed Eng 38:3618-3629, 2010
23. Mutoh T, Ishikawa T, Nishino K, et al: Evaluation of the FloTrac uncalibrated continuous cardiac output system for perioperative hemodynamic monitoring after subarachnoid hemorrhage. J Neurosurg Anesthesiol 21:218-225, 2009
24. Mutoh T, Kazumata K, Ishikawa T, et al: Performance of bedside transpulmonary thermodilution monitoring for goal-directed hemodynamic management after subarachnoid hemorrhage. Stroke 40: 2368-2374, 2009
25. Aboy M, Crespo C, Austin D: An enhanced automatic algorithm for estimation of respiratory variations in arterial pulse pressure during regions of abrupt hemodynamic changes. IEEE Trans Biomed Eng 56: 2537-2545, 2009
26. Raue W, Swierzy M, Koplin G, et al: Comparison of electrical velocimetry and transthoracic thermodilution technique for cardiac output assessment in critically ill patients. Eur J Anaesthesiol 26: 1067-1071, 2009
27. Donati A, Nardella R, Gabbanelli V, et al: The ability of PiCCO versus LiDCO variables to detect changes in cardiac index: A prospective clinical study. Minerva Anestesiol 74:367-374, 2008
28. Compton F, Wittrock M, Schaefer JH, et al: Noninvasive cardiac output determination using applanation tonometry-derived radial artery pulse contour analysis in critically ill patients. Anesth Analg 106: 171-174, 2008
29. Compton FD, Zukunft B, Hoffmann C, et al: Performance of a minimally invasive uncalibrated cardiac output monitoring system (Flotrac/Vigileo) in haemodynamically unstable patients. Br J Anaesth 100:451-456, 2008
30. Zoremba N, Bickenbach J, Krauss B, et al: Comparison of electrical velocimetry and thermodilution techniques for the measurement of cardiac output. Acta Anaesthesiol Scand 51:1314-1319, 2007
31. Sakka SG, Hanusch T, Thuemer O, et al: The influence of venovenous renal replacement therapy on measurements by the transpulmonary thermodilution technique. Anesth Analg 105:1079-1082, 2007
32. Sakka SG, Kozieras J, Thuemer O, et al: Measurement of cardiac output: A comparison between transpulmonary thermodilution and uncalibrated pulse contour analysis. Br J Anaesth 99:337-342, 2007
33. Spohr F, Hettrich P, Bauer H, et al: Comparison of two methods for enhanced continuous circulatory monitoring in patients with septic shock. Intensive Care Med 33:1805-1810, 2007
34. Gabbanelli V, Pantanetti S, Donati A, et al: Initial distribution volume of glucose as noninvasive indicator of cardiac preload: Comparison with intrathoracic blood volume. Intensive Care Med 30: 2067-2073, 2004
35. Hammon M, Dankerl P, Voit-Hohne HL, et al: Improving diagnostic accuracy in assessing pulmonary edema on bedside chest radiographs using a standardized scoring approach. BMC Anesthesiol 14:94, 2014
36. Sakamoto Y, Inoue S, Iwamura T, et al: Usefulness of the endotoxin activity assay to evaluate the degree of lung injury. Yonsei Med J 55:975-979, 2014
37. Saugel B, Meidert AS, Langwieser N, et al: An autocalibrating algorithm for non-invasive cardiac output determination based on the analysis of an arterial pressure waveform recorded with radial artery applanation tonometry: A proof of concept pilot analysis. J Clin Monit Comput 28:357-362, 2014
38. Raymondos K, Molitoris U, Capewell M, et al: Negative- versus positive-pressure ventilation in intubated patients with acute respiratory distress syndrome. Crit Care 16:R37, 2012

39. Krajcova A, Matousek V, Duska F: Mechanism of paracetamol-induced hypotension in critically ill patients: A prospective observational cross-over study. Aust Crit Care 26:136-141, 2013

40. von Delius S, Thies P, Umgelter A, et al: Hemodynamics after endoscopic submucosal injection of epinephrine in patients with nonvariceal upper gastrointestinal bleeding: A matter of concern. Endoscopy 38:1284-1288, 2006

41. Grensemann J, Bruecken U, Treszl A, et al: The influence of prone positioning on the accuracy of calibrated and uncalibrated pulse contour-derived cardiac index measurements. Anesth Analg 116:820-826, 2013

42. Sakka SG: Resuscitation of hemorrhagic shock with normal saline versus lactated Ringer's: Effects on oxygenation, extravascular lung water, and hemodynamics. Crit Care 13:128, 2009

43. Sakka SG, Becher L, Kozieras J, et al: Effects of changes in blood pressure and airway pressures on parameters of fluid responsiveness. Eur J Anaesthesiol 26:322-327, 2009

44. Monnet X, Dres M, Ferre A, et al: Prediction of fluid responsiveness by a continuous non-invasive assessment of arterial pressure in critically ill patients: Comparison with four other dynamic indices. Br J Anaesth 109:330-338, 2012

45. Dong ZZ, Fang Q, Zheng X, et al: Passive leg raising as an indicator of fluid responsiveness in patients with severe sepsis. World J Emerg Med 3:191-196, 2012

46. Gondos T, Marjanek Z, Ulakcsai Z, et al: Short-term effectiveness of different volume replacement therapies in postoperative hypovolaemic patients. Eur J Anaesthesiol 27:794-800, 2010

47. Perner A, Faber T: Stroke volume variation does not predict fluid responsiveness in patients with septic shock on pressure support ventilation. Acta Anaesthesiol Scand 50:1068-1073, 2006

48. Hofer CK, Ganter MT, Matter-Ensner S, et al: Volumetric assessment of left heart preload by thermodilution: comparing the PiCCO-VoLEF system with transoesophageal echocardiography. Anaesthesia 61:316-321, 2006

49. Hofer CK, Furrer L, Matter-Ensner S, et al: Volumetric preload measurement by thermodilution: A comparison with transoesophageal echocardiography. Br J Anaesth 94:748-755, 2005

50. Keller G, Desebbe O, Benard M, et al: Bedside assessment of passive leg raising effects on venous return. J Clin Monit Comput 25: 257-263, 2011

51. Joshi B, Ono M, Brown C, et al: Predicting the limits of cerebral autoregulation during cardiopulmonary bypass. Anesth Analg 114: 503-510, 2012

52. Huber W, Umgelter A, Reindl W, et al: Volume assessment in patients with necrotizing pancreatitis: A comparison of intrathoracic blood volume index, central venous pressure, and hematocrit, and their correlation to cardiac index and extravascular lung water index. Crit Care Med 36:2348-2354, 2008

53. Sakamoto Y, Mashiko K, Saito N, et al: Effectiveness of human atrial natriuretic peptide supplementation in pulmonary edema patients using the pulse contour cardiac output system. Yonsei Med J 51: 354-359, 2010

54. Hung MH, Chan KC, Chang CY, et al: Application of Pulse Contour Cardiac Output (PiCCO) system for adequate fluid management in a patient with severe reexpansion pulmonary edema. Acta Anaesthesiol Taiwan 46:187-190, 2008

55. Oshima K, Kunimoto F, Hinohara H, et al: Evaluation of respiratory status in patients after thoracic esophagectomy using PiCCO system. Ann Thorac Cardiovasc Surg 14:283-288, 2008

56. Oshima K, Kunimoto F, Hinohara H, et al: The evaluation of hemodynamics in post thoracic esophagectomy patients. Hepatogastroenterology 55:1338-1341, 2008

57. Della Rocca G, Costa GM, Coccia C, et al: Preload index: Pulmonary artery occlusion pressure versus intrathoracic blood volume monitoring during lung transplantation. Anesth Analg 95: 835-843, 2002

58. Hofmann-Kiefer K, Chappell D, Jacob M, et al: Acute perioperative hemodilution without using hydroxyethyl starch: Hemodynamic alterations under "controlled" hypovolemia [in German]. Anaesthesist 64:26-32, 2015

59. Zhang Z, Xu X, Yao M, et al: Use of the PiCCO system in critically ill patients with septic shock and acute respiratory distress syndrome: A study protocol for a randomized controlled trial. Trials 14: 32, 2013

60. Zhang G, Mukkamala R: Continuous and minimally invasive cardiac output monitoring by long time interval analysis of a radial arterial pressure waveform: Assessment using a large, public intensive care unit patient database. Br J Anaesth 109:339-344, 2012

61. Gernoth C, Wagner G, Pelosi P, et al: Respiratory and haemodynamic changes during decremental open lung positive end-expiratory pressure titration in patients with acute respiratory distress syndrome. Crit Care 13:R59, 2009

62. Kvalheim VL, Farstad M, Steien E, et al: Infusion of hypertonic saline/starch during cardiopulmonary bypass reduces fluid overload and may impact cardiac function. Acta Anaesthesiol Scand 54:485-493, 2010

63. Gulielmos V, Kappert U, Eller M, et al: Improving hemodynamics by atrial pacing during off-pump bypass surgery. Heart Surg Forum 6:E179-E182, 2003

64. Jones D, Story D, Peyton P, et al: Perioperative pulse contour cardiac output analysis in a patient with severe cardiac dysfunction. Anaesth Intensive Care 34:97-101, 2006

65. Halvorsen PS, Espinoza A, Lundblad R, et al: Agreement between PiCCO pulse-contour analysis, pulmonal artery thermodilution and transthoracic thermodilution during off-pump coronary artery by-pass surgery. Acta Anaesthesiol Scand 50:1050-1057, 2006

66. Halvorsen PS, Sokolov A, Cvancarova M, et al: Continuous cardiac output during off-pump coronary artery bypass surgery: Pulse-contour analyses vs pulmonary artery thermodilution. Br J Anaesth 99: 484-492, 2007

67. Mellert F, Lindner P, Schiller W, et al: Therapeutic optimization of atrioventricular delay in cardiosurgical ICU patients by noninvasive cardiac output measurements versus pulse contour analysis. Thorac Cardiovasc Surgeon 56:269-273, 2008

68. Renner J, Broch O, Duetschke P, et al: Prediction of fluid responsiveness in infants and neonates undergoing congenital heart surgery. Br J Anaesth 108:108-115, 2012

69. Fakler U, Pauli C, Balling G, et al: Cardiac index monitoring by pulse contour analysis and thermodilution after pediatric cardiac surgery. J Thorac Cardiovasc Surg 133:224-228, 2007

70. Hammer S, Loeff M, Reichenspurner H, et al: Effect of cardiopulmonary bypass on myocardial function, damage and inflammation after cardiac surgery in newborns and children. Thorac Cardiovasc Surg 49:349-354, 2001

71. Grosek S, Primozic J, Ihan A, et al: Interleukin-10, T-lymphocytes, and cardiac output in children after ventricular septal defect repair: A pilot study. Intensive Care Med 32:780-784, 2006

72. Costa MG, Girardi L, Pompei L, et al: Perioperative intra- and extravascular volume in liver transplant recipients. Transplant Proc 43: 1098-1102, 2011

73. Costa MG, Chiarandini P, Della Rocca G: Hemodynamics during liver transplantation. Transplant Proc 39:1871-1873, 2007

74. Umgelter A, Reindl W, Geisler F, et al: Effects of TIPS on global end-diastolic volume and cardiac output and renal resistive index in ICU patients with advanced alcoholic cirrhosis. Ann Hepatol 9: 40-45, 2010

75. Torgay A, Pirat A, Akpek E, et al: Pulse contour cardiac output system use in pediatric orthotopic liver transplantation: Preliminary report of nine patients. Transplant Proc 37:3168-3170, 2005
76. Proulx F, Lemson J, Choker G, et al: Hemodynamic monitoring by transpulmonary thermodilution and pulse contour analysis in critically ill children. Pediatr Crit Care Med 12:459-466, 2011
77. Lopez-Herce J, Bustinza A, Sancho L, et al: Cardiac output and blood volume parameters using femoral arterial thermodilution. Pediatr Int 51:59-65, 2009
78. Lopez-Herce J, Ruperez M, Sanchez C, et al: Estimation of the parameters of cardiac function and of blood volume by arterial thermodilution in an infant animal model. Paediatr Anaesth 16: 635-640, 2006
79. Lopez-Herce J, Ruperez M, Sanchez C, et al: Correlation between cardiac output measured by the femoral arterial thermodilution technique pulmonary arterial and that measured by contour pulse analysis in a paediatric animal model. J Clin Monit Comput 20: 19-23, 2006
80. Cecchetti C, Lubrano R, Cristaldi S, et al: Relationship between global end-diastolic volume and cardiac output in critically ill infants and children. Crit Care Med 36:928-932, 2008
81. Cecchetti C, Stoppa F, Vanacore N, et al: Monitoring of intrathoracic volemia and cardiac output in critically ill children. Minerva Anestesiol 69:907-918, 2003
82. Kraft R, Herndon DN, Branski LK, et al: Optimized fluid management improves outcomes of pediatric burn patients. J Surg Res 181:121-128, 2013
83. Aboelatta Y, Abdelsalam A: Volume overload of fluid resuscitation in acutely burned patients using transpulmonary thermodilution technique. J Burn Care Res 34:349-354, 2013
84. Kuntscher MV, Blome-Eberwein S, Pelzer M, et al: Transcardiopulmonary vs pulmonary arterial thermodilution methods for hemodynamic monitoring of burned patients. J Burn Care Rehabil 23: 21-26, 2002
85. Wan L, Naka T, Uchino S, et al: A pilot study of pulse contour cardiac output monitoring in patients with septic shock. Crit Care Resusc 7:165, 2005
86. Pathil A, Stremmel W, Schwenger V, et al: The influence of haemodialysis on haemodynamic measurements using transpulmonary thermodilution in patients with septic shock: An observational study. Eur J Anaesthesiol 30:16-20, 2013
87. Wiessner R, Gierer P, Schaser K, et al: [Microcirculatory failure of sublingual perfusion in septic-shock patients. Examination by OPS imaging and PiCCO monitoring [in German]. Zentralbl Chir 134: 231-236, 2009
88. Ritter S, Rudiger A, Maggiorini M: Transpulmonary thermodilution-derived cardiac function index identifies cardiac dysfunction in acute heart failure and septic patients: An observational study. Crit Care 13:R133, 2009
89. Horie N, Isotani E, Honda S, et al: Impact of aneurysm location on cardiopulmonary dysfunction after subarachnoid hemorrhage. J Stroke Cerebrovasc Dis 23:1795-1804, 2014
90. Tagami T, Kuwamoto K, Watanabe A, et al: Effect of triple-h prophylaxis on global end-diastolic volume and clinical outcomes in patients with aneurysmal subarachnoid hemorrhage. Neurocrit Care 21: 462-469, 2014
91. Metzelder SM, Coburn M, Stoppe C, et al: Accuracy and precision of calibrated arterial pulse contour analysis in patients with subarachnoid hemorrhage requiring high-dose vasopressor therapy: A prospective observational clinical trial. Crit Care 18:R25, 2014
92. Mutoh T, Ishikawa T, Kobayashi S, et al: Performance of Third-generation FloTrac/Vigileo system during hyperdynamic therapy for delayed cerebral ischemia after subarachnoid hemorrhage. Surg Neurol Int 3:99, 2012
93. Watanabe A, Tagami T, Yokobori S, et al: Global end-diastolic volume is associated with the occurrence of delayed cerebral ischemia and pulmonary edema after subarachnoid hemorrhage. Shock 38: 480-485, 2012
94. Wesseling KH, Jansen JR, Settels JJ, et al: Computation of aortic flow from pressure in humans using a nonlinear, three-element model. J Appl Physiol 74:2566-2573, 1993
95. Feltracco P, Biancofiore G, Ori C, et al: Limits and pitfalls of haemodynamic monitoring systems in liver transplantation surgery. Minerva Anestesiol 78:1372-1384, 2012
96. Oren-Grinberg A: The PiCCO monitor. Int Anesthesiol Clin 48: 57-85, 2010
97. Reuter DA, Huang C, Edrich T, et al: Cardiac output monitoring using indicator-dilution techniques: Basics, limits, and perspectives. Anesth Analg 110:799-811, 2010
98. Erlanger J, Hooker DR: An experimental study of blood pressure and of pulse pressure in man. Johns Hopkins Hosp Rep 12: 145-378, 1904
99. Seeley HF: Some methods of deriving cardiac output from central aortic pressure. Proc R Soc Med 66:478-480, 1973
100. Thiele RH, Durieux ME: Arterial waveform analysis for the anesthesiologist: Past, present, and future concepts. Anesth Analg 113: 766-776, 2011
101. Jansen JR, Schreuder JJ, Mulier JP, et al: A comparison of cardiac output derived from the arterial pressure wave against thermodilution in cardiac surgery patients. Br J Anaesth 87: 212-222, 2001
102. Warner HR, Swan HJ, Connolly DC, et al: Quantitation of beat-to-beat changes in stroke volume from the aortic pulse contour in man. J Appl Physiol 5:495-507, 1953
103. Kouchoukos NT, Sheppard LC, McDonald DA: Estimation of stroke volume in the dog by a pulse contour method. Circ Res 26: 611-623, 1970
104. Lennon M: Pulse contour analysis and transpulmonary thermodilution. Australasian Anaesthesia:163-172, 2003
105. Jansen JRC, van den Berg PCM: Cardiac output by thermodilution and arterial pulse contour techniques. In: Pinsky MR, Payen D (eds). Functional Hemodynamic Monitoring. Berlin: Springer-Verlag; 2005:135-152
106. Rodig G, Prasser C, Keyl C, et al: Continuous cardiac output measurement: Pulse contour analysis vs thermodilution technique in cardiac surgical patients. Br J Anaesth 82:525-530, 1999
107. Langewouters GJ, Wesseling KH, Goedhard WJ: The pressure dependent dynamic elasticity of 35 thoracic and 16 abdominal human aortas in vitro described by a five component model. J Biomech 18: 613-620, 1985
108. Pearse RM, Ikram K, Barry J: Equipment review: An appraisal of the LiDCO plus method of measuring cardiac output. Crit Care 8: 190-195, 2004
109. Heerman JR, Segers P, Roosens CD, et al: Echocardiographic assessment of aortic elastic properties with automated border detection in an ICU: In vivo application of the arctangent Langewouters model. Am J Physiol Heart Circ Physiol 288:H2504-H2511, 2005
110. Jellema WT, Imholz BP, Oosting H, et al: Estimation of beat-to-beat changes in stroke volume from arterial pressure: A comparison of two pressure wave analysis techniques during head-up tilt testing in young, healthy men. Clin Auton Res 9:185-192, 1999
111. Jellema WT, Wesseling KH, Groeneveld AB, et al: Continuous cardiac output in septic shock by simulating a model of the aortic input impedance: A comparison with bolus injection thermodilution. Anesthesiology 90:1317-1328, 1999
112. Critchley LA: Self-calibrating pulse contour cardiac output: Do validation studies really show its clinical reliability? Crit Care 13: 123, 2009

113. Laskey WK, Parker HG, Ferrari VA, et al: Estimation of total systemic arterial compliance in humans. J Appl Physiol 69: 112-119, 1990

114. Avolio A, Westerhof BE, Siebes M, et al: Arterial hemodynamics and wave analysis in the frequency and time domains: An evaluation of the paradigms. Med Biol Eng Comput 47:107-110, 2009

115. Westerhof N, Lankhaar JW, Westerhof BE: The arterial Windkessel. Med Biol Eng Comput 47:131-141, 2009

116. de Wilde RB, Breukers RB, van den Berg PC, et al: Monitoring cardiac output using the femoral and radial arterial pressure waveform. Anaesthesia 61:743-746, 2006

117. Godje O, Hoke K, Goetz AE, et al: Reliability of a new algorithm for continuous cardiac output determination by pulse-contour analysis during hemodynamic instability. Crit Care Med 30: 52-58, 2002

118. Wesseling KH, De Wit B, Smith NT: A simple device for the continuous measurement of cardiac output. Adv Cardiovasc Phys 5: 16-52, 1983

119. Dyson KS, Shoemaker JK, Arbeille P, et al: Modelflow estimates of cardiac output compared with Doppler ultrasound during acute changes in vascular resistance in women. Exp Physiol 95: 561-568, 2010

120. Muller L, Candela D, Nyonzyma L, et al: Disagreement between pulse contour analysis and transpulmonary thermodilution for cardiac output monitoring after routine therapeutic interventions in ICU patients with acute circulatory failure. Eur J Anaesthesiol 28: 664-669, 2011

121. Boyle M, Lawrence J, Belessis A, et al: Comparison of dynamic measurements of pulse contour with pulsed heat continuous cardiac output in postoperative cardiac surgical patients. Aust Crit Care 20: 27-32, 2007

122. Yamashita K, Nishiyama T, Yokoyama T, et al: The effects of vasodilation on cardiac output measured by PiCCO. J Cardiothorac Vasc Anesth 22:688-692, 2008

123. Bendjelid K: Hemodynamic monitoring development: Helpful technology or expensive luxury? J Clin Monit Comput 26:337-339, 2012

124. Pratt B, Roteliuk L, Hatib F, et al: Calculating arterial pressure-based cardiac output using a novel measurement and analysis method. Biomed Instrum Technol 41:403-411, 2007

125. Bendjelid K: When to recalibrate the PiCCO? From a physiological point of view, the answer is simple. Acta Anaesthesiol Scand 53:689-690, 2009

126. de Wilde RB, Schreuder JJ, van den Berg PC, et al: An evaluation of cardiac output by five arterial pulse contour techniques during cardiac surgery. Anaesthesia 62:760-768, 2007

127. Slagt C, Malagon I, Groeneveld AB: Systematic review of uncalibrated arterial pressure waveform analysis to determine cardiac output and stroke volume variation. Br J Anaesth 112:626-637, 2014

128. Monnet X, Anguel N, Naudin B, et al: Arterial pressure-based cardiac output in septic patients: Different accuracy of pulse contour and uncalibrated pressure waveform devices. Crit Care 14:R109, 2010

129. Saraceni E, Rossi S, Persona P, et al: Comparison of two methods for cardiac output measurement in critically ill patients. Br J Anaesth 106:690-694, 2011

130. Metzelder S, Coburn M, Fries M, et al: Performance of cardiac output measurement derived from arterial pressure waveform analysis in patients requiring high-dose vasopressor therapy. Br J Anaesth 106: 776-784, 2011

131. Junttila EK, Koskenkari JK, Ohtonen PP, et al: Uncalibrated arterial pressure waveform analysis for cardiac output monitoring is biased by low peripheral resistance in patients with intracranial haemorrhage. Br J Anaesth 107:581-586, 2011

132. Hadian M, Kim HK, Severyn DA, et al: Cross-comparison of cardiac output trending accuracy of LiDCO, PiCCO, FloTrac and pulmonary artery catheters. Crit Care 14:R212, 2010

133. Hashim B, Lerner AB: The FloTrac system—measurement of stroke volume and the assessment of dynamic fluid loading. Int Anesthesiol Clin 48:45-56, 2010

134. De Backer D, Marx G, Tan A, et al: Arterial pressure-based cardiac output monitoring: A multicenter validation of the third-generation software in septic patients. Intensive Care Med 37: 233-240, 2011

135. Broch O, Renner J, Hocker J, et al: Uncalibrated pulse power analysis fails to reliably measure cardiac output in patients undergoing coronary artery bypass surgery. Crit Care 15:R76, 2011

136. Donati A, Carsetti A, Tondi S, et al: Thermodilution vs pressure recording analytical method in hemodynamic stabilized patients. J Crit Care 29:260-264, 2014

137. Critchley LA, Lee A, Ho AM: A critical review of the ability of continuous cardiac output monitors to measure trends in cardiac output. Anesth Analg 111:1180-1192, 2010

138. Desebbe O, Henaine R, Keller G, et al: Ability of the third-generation FloTrac/Vigileo software to track changes in cardiac output in cardiac surgery patients: A polar plot approach. J Cardiothorac Vasc Anesth 27:1122-1127, 2013

139. Biancofiore G, Critchley LA, Lee A, et al: Evaluation of a new software version of the FloTrac/Vigileo (version 3.02) and a comparison with previous data in cirrhotic patients undergoing liver transplant surgery. Anesth Analg 113:515-522, 2011

140. Biancofiore G, Critchley LA, Lee A, et al: Evaluation of an uncalibrated arterial pulse contour cardiac output monitoring system in cirrhotic patients undergoing liver surgery. Br J Anaesth 102: 47-54, 2009

141. Biais M, Nouette-Gaulain K, Cottenceau V, et al: Cardiac output measurement in patients undergoing liver transplantation: Pulmonary artery catheter versus uncalibrated arterial pressure waveform analysis. Anesth Analg 106:1480-1486, 2008

142. Critchley LA: Pulse contour analysis: Is it able to reliably detect changes in cardiac output in the haemodynamically unstable patient? Crit Care 15:106, 2011

143. Critchley LA: Validation of the MostCare pulse contour cardiac output monitor: Beyond the Bland and Altman Plot. Anesth Analg 113: 1292-1294, 2011

144. Monnet X, Vaquer S, Anguel N, et al: Comparison of pulse contour analysis by Pulsioflex and Vigileo to measure and track changes of cardiac output in critically ill patients. Br J Anaesth 114: 235-243, 2015

145. Gondos T, Marjanek Z, Kisvarga Z, et al: Precision of transpulmonary thermodilution: How many measurements are necessary? Eur J Anaesthesiol 26:508-512, 2009

146. Bock JC, Deuflhard P, Hoeft A, et al: Evaluation of monoexponential extrapolation of transpulmonary thermal-dye kinetics by use of a new model-free deconvolution algorithm. Med Instrum 22: 20-28, 1988

147. Della Rocca G, Costa MG, Coccia C, et al: Cardiac output monitoring: Aortic transpulmonary thermodilution and pulse contour analysis agree with standard thermodilution methods in patients undergoing lung transplantation. Can J Anaesth 50:707-711, 2003

148. Della Rocca G, Costa MG, Pompei L, et al: Continuous and intermittent cardiac output measurement: Pulmonary artery catheter versus aortic transpulmonary technique. Br J Anaesth 88:350-356, 2002

149. Siranovic M, Kovac J, Gopcevic A, et al: Constant cardiac output monitoring using the PiCCO and LiDCO methods versus PAK in septic patients: When to do calibration? Acta Clin Croat 50: 267-272, 2011

150. Sakka SG, Reuter DA, Perel A: The transpulmonary thermodilution technique. J Clin Monit Comput 26:347-353, 2012
151. Jansen JR: Standard pulse contour methods are not applicable in animals. Intensive Care Med 32:2084-2085 [author reply 2086-2087], 2006
152. Harris AP, Miller CF, Beattie C, et al: The slowing of sinus rhythm during thermodilution cardiac output determination and the effect of altering injectate temperature. Anesthesiology 63: 540-541, 1985
153. Lewis FJ, Deller S, Quinn M, et al: Continuous patient monitoring with a small digital computer. Comput Biomed Res 5: 411-428, 1972
154. Heise D, Faulstich M, Morer O, et al: Influence of continuous renal replacement therapy on cardiac output measurement using thermodilution techniques. Minerva Anestesiol 78:315-321, 2012
155. Faybik P, Hetz H, Baker A, et al: Iced versus room temperature injectate for assessment of cardiac output, intrathoracic blood volume, and extravascular lung water by single transpulmonary thermodilution. J Crit Care 19:103-107, 2004
156. Huber W, Kraski T, Haller B, et al: Room-temperature vs iced saline indicator injection for transpulmonary thermodilution. J Crit Care 29:1133.e7-1133.e14, 2014
157. Rivers EP, Coba V, Whitmill M: Early goal-directed therapy in severe sepsis and septic shock: A contemporary review of the literature. Curr Opin Anaesthesiol 21:128-140, 2008
158. Shorr AF, Micek ST, Jackson WL Jr, et al: Economic implications of an evidence-based sepsis protocol: Can we improve outcomes and lower costs? Crit Care Med 35:1257-1262, 2007
159. Sebat F, Johnson D, Musthafa AA, et al: A multidisciplinary community hospital program for early and rapid resuscitation of shock in nontrauma patients. Chest 127:1729-1743, 2005
160. Kortgen A, Niederprum P, Bauer M: Implementation of an evidence-based "standard operating procedure" and outcome in septic shock. Crit Care Med 34:943-949, 2006
161. Shoemaker WC, Appel PL, Kram HB: Role of oxygen debt in the development of organ failure sepsis, and death in high-risk surgical patients. Chest 102:208-215, 1992
162. Shoemaker WC, Appel PL, Kram HB: Tissue oxygen debt as a determinant of postoperative organ failure. Prog Clin Biol Res 308: 133-136, 1989
163. Shoemaker WC, Appel PL, Kram HB: Tissue oxygen debt as a determinant of lethal and nonlethal postoperative organ failure. Crit Care Med 16:1117-1120, 1988
164. Price JD, Sear JW, Venn RM: Perioperative fluid volume optimization following proximal femoral fracture. Cochrane Database Syst Rev (1):CD003004, 2004
165. Giglio MT, Marucci M, Testini M, et al: Goal-directed haemodynamic therapy and gastrointestinal complications in major surgery: A meta-analysis of randomized controlled trials. Br J Anaesth 103:637-646, 2009
166. Abbas SM, Hill AG: Systematic review of the literature for the use of oesophageal Doppler monitor for fluid replacement in major abdominal surgery. Anaesthesia 63:44-51, 2008
167. Pearse R, Dawson D, Fawcett J, et al: Early goal-directed therapy after major surgery reduces complications and duration of hospital stay. A randomised, controlled trial [ISRCTN38797445]. Crit Care 9:R687-R693, 2005
168. Lassen K, Soop M, Nygren J, et al: Consensus review of optimal perioperative care in colorectal surgery: Enhanced Recovery After Surgery (ERAS) Group recommendations. Arch Surg 144: 961-969, 2009
169. Varadhan KK, Neal KR, Dejong CH, et al: The enhanced recovery after surgery (ERAS) pathway for patients undergoing major elective open colorectal surgery: A meta-analysis of randomized controlled trials. Clin Nutr 29:434-440, 2010
170. Chikhani M, Moppett IK: Minimally invasive cardiac output monitoring: What evidence do we need? Br J Anaesth 106: 451-453, 2011
171. Brammar A, Nicholson A, Trivella M, et al: Perioperative fluid volume optimization following proximal femoral fracture. Cochrane Database Syst Rev 9:CD003004, 2013
172. Gurgel ST, do Nascimento P Jr: Maintaining tissue perfusion in high-risk surgical patients: A systematic review of randomized clinical trials. Anesth Analg 112:1384-1391, 2011
173. Hamilton MA, Cecconi M, Rhodes A: A systematic review and meta-analysis on the use of preemptive hemodynamic intervention to improve postoperative outcomes in moderate and high-risk surgical patients. Anesth Analg 112:1392-1402, 2011
174. Rivers E, Nguyen B, Havstad S, et al: Early goal-directed therapy in the treatment of severe sepsis and septic shock. N Engl J Med 345:1368-1377, 2001
175. Mehta N, Fernandez-Bustamante A, Seres T: A review of intraoperative goal-directed therapy using arterial waveform analysis for assessment of cardiac output. ScientificWorldJournal 2014: 702964, 2014
176. Pearse RM, Harrison DA, MacDonald N, et al: Effect of a perioperative, cardiac output-guided hemodynamic therapy algorithm on outcomes following major gastrointestinal surgery: A randomized clinical trial and systematic review. JAMA 311:2181-2190, 2014
177. Vincent JL, Rhodes A, Perel A, et al: Clinical review: Update on hemodynamic monitoring—a consensus of 16. Crit Care 15: 229, 2011
178. Uchino S, Bellomo R, Morimatsu H, et al: Pulmonary artery catheter versus pulse contour analysis: A prospective epidemiological study. Crit Care 10:R174, 2006
179. Sakka SG, van Hout N: Relation between indocyanine green (ICG) plasma disappearance rate and ICG blood clearance in critically ill patients. Intensive Care Med 32:766-769, 2006
180. Goepfert MS, Reuter DA, Akyol D, et al: Goal-directed fluid management reduces vasopressor and catecholamine use in cardiac surgery patients. Intensive Care Med 33:96-103, 2007
181. Goepfert MS, Richter HP, Zu Eulenburg C, et al: Individually optimized hemodynamic therapy reduces complications and length of stay in the intensive care unit: A prospective, randomized controlled trial. Anesthesiology 119:824-836, 2013
182. Downs EA, Isbell JM: Impact of hemodynamic monitoring on clinical outcomes. Best Pract Res Clin Anaesthesiol 28:463-476, 2014
183. de Wilde RPB, van den Berg PC, Jansen JR: Review of the PiCCO device; our experience in the ICU. Netherlands J Crit Care 12: 177-179, 2008
184. Jansen JR, Wesseling KH, Settels JJ, et al: Continuous cardiac output monitoring by pulse contour during cardiac surgery. Eur Heart J 11(Suppl I):26-32, 1990
185. Segal E, Katzenelson R, Berkenstadt H, et al: Transpulmonary thermodilution cardiac output measurement using the axillary artery in critically ill patients. J Clin Anesth 14:210-213, 2002
186. Pulsion. Available at: http://www.pulsion.com. Accessed June 10, 2014
187. Antonini M, Meloncelli S, Dantimi C, et al: The PiCCO system with brachial-axillary artery access in hemodynamic monitoring during surgery of abdominal aortic aneurysm [in Italian]. Minerva Anestesiol 67:447-456, 2001
188. Orme RM, Pigott DW, Mihm FG: Measurement of cardiac output by transpulmonary arterial thermodilution using a long radial artery catheter. A comparison with intermittent pulmonary artery thermodilution. Anaesthesia 59:590-594, 2004

189. Clementi G: Hemodynamic monitoring using a long radial catheter [in Italian]. Minerva Anestesiol 68:231-235, 2002
190. Belda FJ, Aguilar G, Teboul JL, et al: Complications related to less-invasive haemodynamic monitoring. Br J Anaesth 106: 482-486, 2011
191. Scheer B, Perel A, Pfeiffer UJ: Clinical review: Complications and risk factors of peripheral arterial catheters used for haemodynamic monitoring in anaesthesia and intensive care medicine. Crit Care 6: 199-204, 2002
192. Horlocker TT, Bishop AT: Compartment syndrome of the forearm and hand after brachial artery cannulation. Anesth Analg 81: 1092-1094, 1995
193. Bagga V, Palmer M, Sadasivan R, et al: Volkman's contracture, persistent limb ischaemia, and amputation: A complication of brachial artery catheterisation for haemodynamic monitoring using PiCCO. Case Rep Crit Care 2013:1-3, 2013
194. Borrego R, Lopez-Herce J, Mencia S, et al: Severe ischemia of the lower limb and of the intestine associated with systemic vasoconstrictor therapy and femoral arterial catheterization. Pediatr Crit Care Med 7:267-269, 2006
195. Ong T, Gillies MA, Bellomo R: Failure of continuous cardiac output measurement using the PiCCO Device during induced hypothermia: A case report. Crit Care Resusc 6:99-101, 2004
196. Janda M, Scheeren TW, Bajorat J, et al: The impact of intra-aortic balloon pumping on cardiac output determination by pulmonary arterial and transpulmonary thermodilution in pigs. J Cardiothorac Vasc Anesth 20:320-324, 2006
197. Giraud R, Siegenthaler N, Park C, et al: Transpulmonary thermodilution curves for detection of shunt. Intensive Care Med 36: 1083-1086, 2010
198. Schmidt S, Westhoff TH, Hofmann C, et al: Effect of the venous catheter site on transpulmonary thermodilution measurement variables. Crit Care Med 35:783-786, 2007
199. Schmidt S, Westhoff TH, Compton F, et al: Avoiding the cross-talk phenomenon when assessing cardiac output using the transpulmonary thermodilution technique via the femoral vein access. Crit Care Med 35:2670, 2007
200. Michard F: Looking at transpulmonary thermodilution curves: The cross-talk phenomenon. Chest 126:656-657, 2004
201. Bendjelid K: Avoiding the cross-talk phenomenon when assessing cardiac output using the transpulmonary thermodilution technique via the femoral vein access. Crit Care Med 35:2670, 2007
202. Michard F, Schachtrupp A, Toens C: Factors influencing the estimation of extravascular lung water by transpulmonary thermodilution in critically ill patients. Crit Care Med 33:1243-1247, 2005
203. Buhre W, Weyland A, Kazmaier S, et al: Comparison of cardiac output assessed by pulse-contour analysis and thermodilution in patients undergoing minimally invasive direct coronary artery bypass grafting. J Cardiothorac Vasc Anesth 13:437-440, 1999
204. Hamzaoui O, Monnet X, Richard C, et al: Effects of changes in vascular tone on the agreement between pulse contour and transpulmonary thermodilution cardiac output measurements within an up to 6-hour calibration-free period. Crit Care Med 36:434-440, 2008
205. Irlbeck M, Forst H, Briegel J, et al: Continuous measurement of cardiac output with pulse contour analysis [in German]. Anaesthesist 44:493-500, 1995
206. Bein B, Renner J, Meybohm P, et al: Validation of pulse contour derived stroke volume variation. Br J Anaesth 99: 745-746, [author reply 746] 2007
207. Bein B, Meybohm P, Cavus E, et al: The reliability of pulse contour-derived cardiac output during hemorrhage and after vasopressor administration. Anesth Analg 105:107-113, 2007
208. Buhre W, Rex S: Is continuous really continuous? Crit Care Med 36:628-630, 2008
209. Sander M, Spies CD, Grubitzsch H, et al: Comparison of uncalibrated arterial waveform analysis in cardiac surgery patients with thermodilution cardiac output measurements. Crit Care 10: R164, 2006
210. Sander M, von Heymann C, Foer A, et al: Pulse contour analysis after normothermic cardiopulmonary bypass in cardiac surgery patients. Crit Care 9:R729-R734, 2005
211. Schuerholz T, Meyer MC, Friedrich L, et al: Reliability of continuous cardiac output determination by pulse-contour analysis in porcine septic shock. Acta Anaesthesiol Scand 50:407-413, 2006
212. Gruenewald M, Renner J, Meybohm P, et al: Reliability of continuous cardiac output measurement during intra-abdominal hypertension relies on repeated calibrations: An experimental animal study. Crit Care 12:R132, 2008
213. Johansson A, Chew M: Reliability of continuous pulse contour cardiac output measurement during hemodynamic instability. J Clin Monit Comput 21:237-242, 2007
214. Cecconi M, Dawson D, Casaretti R, et al: A prospective study of the accuracy and precision of continuous cardiac output monitoring devices as compared to intermittent thermodilution. Minerva Anestesiol 76:1010-1017, 2010
215. Bein B, Worthmann F, Tonner PH, 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 Anesth 18:185-189, 2004
216. Sami A, Sami A, Rochdil N, et al: PiCCO monitoring accuracy in low body temperature. Am J Emerg Med 25:845-846, 2007
217. Holm C, Mayr M, Horbrand F, et al: Reproducibility of transpulmonary thermodilution measurements in patients with burn shock and hypothermia. J Burn Care Rehabil 26:260-265, 2005
218. Chamos C, Vele L, Hamilton M, et al: Less invasive methods of advanced hemodynamic monitoring: Principles, devices, and their role in the perioperative hemodynamic optimization. Perioper Med (Lond) 2:19, 2013
219. Sondergaard S: Pavane for a pulse pressure variation defunct. Crit Care 17:327, 2013
220. Godje O, Peyerl M, Seebauer T, et al: Reproducibility of double indicator dilution measurements of intrathoracic blood volume compartments, extravascular lung water, and liver function. Chest 113: 1070-1077, 1998
221. Kiefer N, Hofer CK, Marx G, et al: Clinical validation of a new thermodilution system for the assessment of cardiac output and volumetric parameters. Crit Care 16:R98, 2012
222. Newman EV, Merrell M, Genecin A, et al: The dye dilution method for describing the central circulation. An analysis of factors shaping the time-concentration curves. Circulation 4:735-746, 1951
223. Michard F, Alaya S, Zarka V, et al: Global end-diastolic volume as an indicator of cardiac preload in patients with septic shock. Chest 124:1900-1908, 2003
224. Sakka SG, Ruhl CC, Pfeiffer UJ, et al: Assessment of cardiac preload and extravascular lung water by single transpulmonary thermodilution. Intensive Care Med 26:180-187, 2000
225. Sakka SG, Bredle DL, Reinhart K, et al: Comparison between intrathoracic blood volume and cardiac filling pressures in the early phase of hemodynamic instability of patients with sepsis or septic shock. J Crit Care 14:78-83, 1999
226. Mutoh T, Kazumata K, Ajiki M, et al: Goal-directed fluid management by bedside transpulmonary hemodynamic monitoring after subarachnoid hemorrhage. Stroke 38:3218-3224, 2007
227. Wiesenack C, Prasser C, Keyl C, et al: Assessment of intrathoracic blood volume as an indicator of cardiac preload: Single transpulmonary thermodilution technique versus assessment of pressure preload parameters derived from a pulmonary artery catheter. J Cardiothorac Vasc Anesth 15:584-588, 2001

228. Lenkin AI, Kirov MY, Kuzkov VV, et al: Comparison of goal-directed hemodynamic optimization using pulmonary artery catheter and transpulmonary thermodilution in combined valve repair: A randomized clinical trial. Crit Care Res Pract 2012:821218, 2012

229. Wolf S, Riess A, Landscheidt JF, et al: Global end-diastolic volume acquired by transpulmonary thermodilution depends on age and gender in awake and spontaneously breathing patients. Crit Care 13: R202, 2009

230. Muller L, Louart G, Bengler C, et al: The intrathoracic blood volume index as an indicator of fluid responsiveness in critically ill patients with acute circulatory failure: A comparison with central venous pressure. Anesth Analg 107:607-613, 2008

231. Marik PE, Cavallazzi R, Vasu T, et al: Dynamic changes in arterial waveform derived variables and fluid responsiveness in mechanically ventilated patients: A systematic review of the literature. Crit Care Med 37:2642-2647, 2009

232. Sakka SG: Extravascular lung water in ARDS patients. Minerva Anestesiol 79:274-284, 2013

233. Michard F: Bedside assessment of extravascular lung water by dilution methods: Temptations and pitfalls. Crit Care Med 35: 1186-1192, 2007

234. Gupta R, Newbould R, Matthews P: Methods of measuring lung water. J Intensive Care Soc 13:209-215, 2012

235. Brown LM, Calfee CS, Howard JP, et al: Comparison of thermodilution measured extravascular lung water with chest radiographic assessment of pulmonary oedema in patients with acute lung injury. Ann Intensive Care 3:25, 2013

236. Brown LM, Liu KD, Matthay MA: Measurement of extravascular lung water using the single indicator method in patients: Research and potential clinical value. Am J Physiol Lung Cell Mol Physiol 297: L547-L558, 2009

237. Kirov MY, Kuzkov VV, Kuklin VN, et al: Extravascular lung water assessed by transpulmonary single thermodilution and postmortem gravimetry in sheep. Crit Care 8:R451-R458, 2004

238. Mihm FG, Feeley TW, Jamieson SW: Thermal dye double indicator dilution measurement of lung water in man: Comparison with gravimetric measurements. Thorax 42:72-76, 1987

239. Mihm FG, Feeley TW, Rosenthal MH, et al: Measurement of extravascular lung water in dogs using the thermal-green dye indicator dilution method. Anesthesiology 57:116-122, 1982

240. Kushimoto S, Taira Y, Kitazawa Y, et al: The clinical usefulness of extravascular lung water and pulmonary vascular permeability index to diagnose and characterize pulmonary edema: A prospective multicenter study on the quantitative differential diagnostic definition for acute lung injury/acute respiratory distress syndrome. Crit Care 16:R232, 2012

241. Tagami T, Kushimoto S, Tosa R, et al: The precision of PiCCO measurements in hypothermic post-cardiac arrest patients. Anaesthesia 67:236-243, 2012

242. Tagami T, Kushimoto S, Yamamoto Y, et al: Validation of extravascular lung water measurement by single transpulmonary thermodilution: Human autopsy study. Crit Care 14:R162, 2010

243. Kushimoto S, Endo T, Yamanouchi S, et al: Relationship between extravascular lung water and severity categories of acute respiratory distress syndrome by the Berlin definition. Crit Care 17:R132, 2013

244. Chew MS, Ihrman L, During J, et al: Extravascular lung water index improves the diagnostic accuracy of lung injury in patients with shock. Crit Care 16:R1, 2012

245. Chew MS: Extravascular lung water in acute respiratory distress syndrome and the Berlin definition: Time for real change. Crit Care 17: 463, 2013

246. Phillips CR: The Berlin definition: Real change or the emperor's new clothes? Crit Care 17:174, 2013

247. Mallat J: Is extravascular lung water index useful for the diagnostic accuracy of lung injury in patients with shock? We need more evidence. Crit Care 16:420, 2012

248. Mallat J: Can extravascular lung water predict progression to acute lung injury in patients at increased risk? Still an unanswered question. Crit Care Med 40:1391-1392, 2012

249. Jozwiak M, Silva S, Persichini R, et al: Extravascular lung water is an independent prognostic factor in patients with acute respiratory distress syndrome. Crit Care Med 41:472-480, 2013

250. Martin GS, Eaton S, Mealer M, et al: Extravascular lung water in patients with severe sepsis: A prospective cohort study. Crit Care 9: R74-R82, 2005

251. Craig TR, Duffy MJ, Shyamsundar M, et al: Extravascular lung water indexed to predicted body weight is a novel predictor of intensive care unit mortality in patients with acute lung injury. Crit Care Med 38: 114-120, 2010

252. Huang CC, Kao KC, Fu JY, et al: Effects of extravascular lung water on the measurement of transpulmonary thermodilution cardiac output in acute respiratory distress syndrome patients. J Cardiothorac Vasc Anesth 25:481-485, 2011

253. Roch A, Michelet P, Lambert D, et al: Accuracy of the double indicator method for measurement of extravascular lung water depends on the type of acute lung injury. Crit Care Med 32:811-817, 2004

254. Effros RM, Pornsuriyasak P, Porszasz J, et al: Indicator dilution measurements of extravascular lung water: Basic assumptions and observations. Am J Physiol Lung Cell Mol Physiol 294: L1023-L1031, 2008

255. Kahn SR, Panju A, Geerts W, et al: Multicenter evaluation of the use of venous thromboembolism prophylaxis in acutely ill medical patients in Canada. Thromb Res 119:145-155, 2007

256. Kambara K, Jerome EH, Serikov VB, et al: Reliability of extravascular lung thermal volume measurements by thermal conductivity technique in sheep. J Appl Physiol 73:1449-1456, 1992

257. Combes A, Berneau JB, Luyt CE, et al: Estimation of left ventricular systolic function by single transpulmonary thermodilution. Intensive Care Med 30:1377-1383, 2004

258. Meybohm P, Gruenewald M, Renner J, et al: Assessment of left ventricular systolic function during acute myocardial ischemia: A comparison of transpulmonary thermodilution and transesophageal echocardiography. Minerva Anestesiol 77:132-141, 2011

259. Perny J, Kimmoun A, Perez P, et al: Evaluation of cardiac function index as measured by transpulmonary thermodilution as an indicator of left ventricular ejection fraction in cardiogenic shock. Biomed Res Int 2014:1-7, 2014

260. Katzenelson R, Perel A, Berkenstadt H, et al: Accuracy of transpulmonary thermodilution versus gravimetric measurement of extravascular lung water. Crit Care Med 32:1550-1554, 2004

261. Reuter DA, Felbinger TW, Moerstedt K, et al: Intrathoracic blood volume index measured by thermodilution for preload monitoring after cardiac surgery. J Cardiothorac Vasc Anesth 16:191-195, 2002

262. Bogert LW, Wesseling KH, Schraa O, et al: Pulse contour cardiac output derived from non-invasive arterial pressure in cardiovascular disease. Anaesthesia 65:1119-1125, 2010