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Minimally Invasive Hemodynamic Monitoring in Intensive Care Unit. A Brief Review

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Abstract

To avoid use of a Swan-Ganz catheter and its attendant complications, new technologies have now become available to help the clinician perform a less invasive hemodynamic monitoring in patients in the intensive care unit (ICU). Among these, conventional echocardiography, the esophageal Doppler, pulse pressure analysis, the transpulmonary thermodilution, the indicator dilution and the thoracic electrical bioimpedance and bioreactance, all aim at measuring stroke volume and cardiac output by less invasive means and they are herein briefly reviewed.

Key Words: hemodynamic monitoring; cardiac output; stroke volume; echocardiography; Doppler

Abbreviations: CO = cardiac output; CVP = central venous pressure; ICU = intensive care unit; PAC = pulmonary artery catheter; SV = stroke volume; VTI = velocity time integral

Introduction

Multi-organ dysfunction commonly seen in critically ill patients as a consequence of systemic inflammatory response syndrome or sepsis, is mediated by an imbalance between oxygen delivery and demand, which inevitably leads to tissue hypoxia and shock. In this pathophysiological procedure, circulatory parameters such as preload, afterload and myocardial contractility play a cardinal role. Traditionally, vital signs, physical findings, central venous pressure, arterial oxygen saturation and urine output have been used to assess volume status and tissue oxygenation. The need for early hemodynamic assessment and consequent strict goal-directed specific treatment has been recognized since 2001 and it has been shown to provide better outcomes in septic patients.[1] Unfortunately, the aforementioned variables do not change significantly in the early stages of shock, and are not considered suitable for advanced hemodynamic evaluation.[2] Volume replacement is usually the first step in resuscitation; however not all hemodynamically unstable patients are volume-responsive, and fluid overload can have deleterious effects.[3] Thus, the aim of the hemodynamic assessment would be to recognize volume depletion (cardiac preload estimation) and predict the response to fluid administration. The desirable outcome of such an action is increase of stroke volume (SV) and cardiac output (CO).

Therefore, monitoring of these parameters can provide the most reliable information. After the introduction of pulmonary artery catheter (PAC) by Swan and Ganz in the 1970s, which could obtain reliable intracardiac pressure and CO measurements, right heart catheterization dominated clinical practice until the mid 1990s, when Connors et al reported increased mortality related to the PAC use in the ICU setting.[4] Since then, several minimally invasive or non-invasive methods to measure CO and evaluate other hemodynamic parameters in order to assess volume status or predict fluid responsiveness have emerged, each trying to find a place in everyday routine of ICUs. Namely, they include the esophageal Doppler, the conventional echocardiography, the pulse pressure analysis, the transpulmonary thermodilution, the indicator dilution and the thoracic electrical bioimpedance and bioreactance and they will be briefly discussed here.

Non-invasive modalities

Esophageal Doppler

From the mid-esophageal descending aorta long axis view one can measure the blood flow velocity. The CO calculation requires the aortic diameter which can be either measured or estimated on the basis of physical characteristics of the specific person, and takes into account the distribution of blood to the descending aorta.[5] Although readily available, this method has some significant limitations. Firstly, it can be technically demanding with regard to the proper image acquisition. Moreover, the aortic diameter may vary over time, influenced by vascular tone, aortic compliance or vasopressor use, and the assumption that descending aorta receives a predetermined part of stroke volume may introduce considerable error in the measurement.[6] However, esophageal Doppler is reliable in detecting changes in CO [7] and it has been shown to provide morbidity benefit when used to guide fluid administration in the operating theatre. [8-10]

Transthoracic echocardiography

Conventional and novel techniques can provide valuable information of left and right ventricular function, inferior vena cava dimensions which serve as a measure of preload and CO approached by calculating the velocity-time integral (VTI) of left ventricular outflow tract. [11-12]

Pulse contour analysis

Several systems which compute SV and CO based on the waveform of arterial pressure have been developed. All use algorithms that incorporate assumptions of systemic vascular resistance and arterial compliance to produce a realistic pressure-volume relationship. The central hypothesis states that SV is proportional to the arterial pulse pressure [13] and although aortic compliance is a non-linear function of blood pressure, SV is calculated from the

area under the curve of the systolic portion of the arterial waveform (**Fig**. 1.) with the use of sophisticated mathematical methods.[14] It is obvious that in order to guarantee the reliability of measurements, the arterial pressure tracing must be optimal and that conditions that affect the relationship between pulse pressure and SV (aortic regurgitation, intra-aortic balloon counterpulsation) will interfere and modify the results. [15]

The commercially available systems fall into 3 categories: (1) systems that require demographic and somatometric data to estimate arterial impedance, (2) systems that require no additional information and (3) systems that require periodic calibration by objective CO measurement using thermodilution or indicator dilution method.

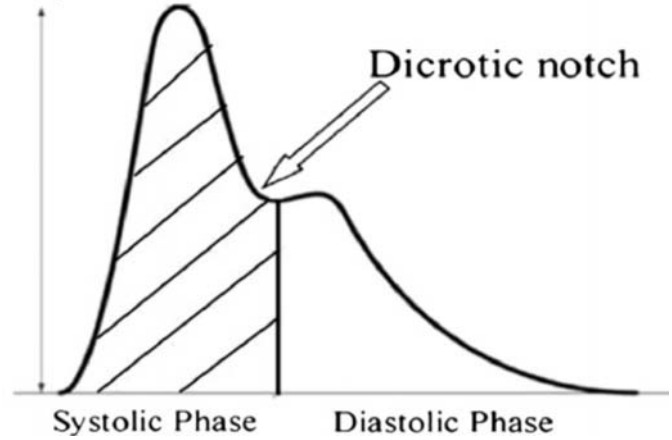

Figure 1. Area under the curve of systolic part of arterial waveform is used to obtain stroke volume measurement

Uncalibrated devices

The FloTrac system includes a sensor connected to the Vigileo monitor. It obtains the arterial pulse signal from an indwelling arterial catheter, irrespective of its position, and calculates the SV and subsequently the CO assuming a linear relationship between SV and pulse pressure. The raw data, produced by arterial waveform sampling, are corrected with respect to arterial compliance, mean arterial pressure and waveform characteristics, by a conversion factor. Arterial compliance is estimated using demographic and somatometric values. Waveform features to be evaluated are skewness (asymmetry) and kyrtosis (peakedness) and are thought to represent changes in vascular tone. The system's reliability has been tested against the presumed gold standard (pulmonary catheter thermodilution) and the latest upgraded third generation editions proved more trustworthy than the previous ones. However, its accuracy fades away when the patient receives substantial amounts of vasopressors and it does not detect accurately the changes in SV after a fluid challenge.[6, 16-18] In a clinical trial, the early use of FloTrac system in hemodynamically unstable ICU patients neither led to faster stabilization nor improved outcome. [19] These weaknesses may have been overcome by the 4th generation devices but more trials are necessary to allow for conclusive statements. [20]

The MostCare system needs no additional data and determines SV by measuring the area under the curve during the whole cardiac cycle. This method is called Pressure recording analytical method (PRAM). The device disintegrates the waveform into its systolic and diastolic phase identifying the dicrotic notch and then determines the contribution of each phase and calculates two impedances. This procedure, with the use of advanced mathematical algorithms allows for an internal calibration as the elastic properties of the arteries can be approximated instantaneously by the waveform analysis. [21] Although an easy and minimally invasive method, its evaluation against the standard techniques has yielded conflicting results, with most weaknesses appearing when applied on hemodynamically unstable patients. [22-29]

A new entry in the area of non-invasive CO monitoring is the Nexfin monitor. The device consists of an inflatable cuff which is placed around the middle phalanx of a finger and connected to the monitor. The cuff retains the volume of the finger constant by applying the appropriate amount of pressure continuously, thus producing a pressure waveform. This finger artery pressure is then used to deduce the brachial artery waveform, using coefficients which are derived from extensive clinical data. The method has been evaluated during cardiac surgery and in the emergency department and its comparison with echocardiographic methods and transpulmonary thermodilution has yielded promising results. Interestingly, it seems to maintain its reliability in cases of vasopressor administration. In critically ill patients, it can measure blood pressure with acceptable accuracy compared to invasive systems but showed moderate correlation with transpulmonary thermodilution in estimation of CO. [30-36]

Calibrated devices

These systems perform continuous measurement of arterial pressure, SV and CO by analyzing the arterial pressure waveform obtained from a peripheral or preferably central arterial line, and recalibrate intermittently using an indicator dilution or thermodilution method. The LiDCO technology utilizes the lithium dilution technique (**Fig**. 2). A certain amount of lithium chloride (0.5-2 mL) is injected through a peripheral or central line and the lithium concentration is measured at the arterial catheter site, using a Li+-sensitive electrode. This electrode traces other monovalent cations as well, such as sodium, and hence a correction factor with respect to sodium plasma levels is used. Therapeutic lithium

administration and muscle relaxants such as atracurium and rocuronium can interact with the Lithium sensor and affect the results because they contain a positively charged quaternary ammonia ion that can be detected by the electrode. The reliability of the method has been validated in several clinical settings and has been found to exert a good correlation in CO measurement with pulmonary artery catheter in critically ill patients with impaired left ventricular function after cardiac surgery and in cases of hyperdynamic conditions. [37,38] It is advised to recalibrate the device at regular intervals (e.g. every 6-8 hours), when acute hemodynamic changes have occurred or vasoactive medications have been administered to the patient. [6]

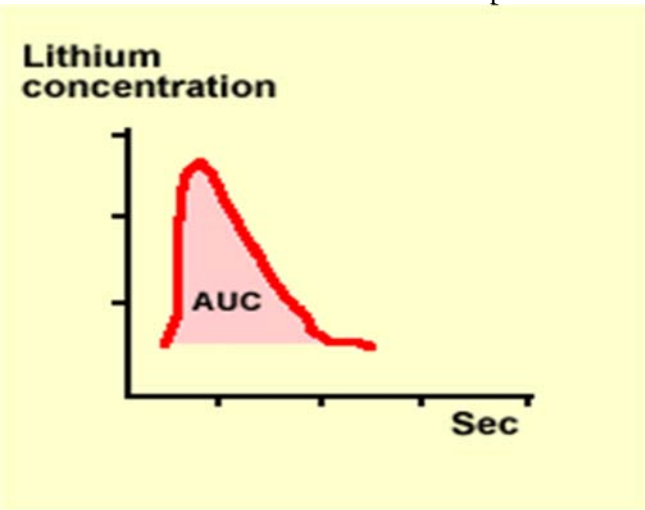

Figure 2. Lithium dilution curve during LiDCO system calibration.

The PiCCO monitoring device calculates blood pressure, SV and CO by arterial waveform interpretation and uses transpulmonary thermodilution to perform intermittent CO calibration. It requires a central venous line and a specific femoral arterial catheter. Cold saline is injected through the venous access site and temperature is measured by the femoral artery catheter. Cardiac output is derived using the thermodilution equation:

$$CO = \frac{(T_B - T_I) \times K}{\int_0^\infty \Delta T_B(t)dt}$$

Where Tb = blood temperature, Ti = injectate temperature, and K=computation constant.

The time-temperature curve is slightly different than that obtained by pulmonary artery thermodilution (**Fig**. 3). For the continuous CO measurement the system needs the shape of the arterial waveform (dP/dt), arterial compliance, systemic vascular resistance (SVR), and a patient-specific calibration factor. Stroke volume is derived by analyzing the systolic portion of the arterial waveform. Vascular compliance is estimated from SVR and the diastolic portion of the arterial waveform. Recalibration is necessary every 6-8 hours to allow for reliable continuous real time results. Furthermore, PiCCO can provide additional information, namely the global end-diastolic volume (GEDV), which represents preload more reliably than the CVP, the intrathoracic blood volume (ITBV), the extravascular lung water (EVLW), and the pulmonary vascular permeability index (PVPI). These data are calculated using sophisticated mathematical formulas and can help the clinician discriminate between cardiogenic pulmonary edema and non-cardiogenic forms. [39-41]

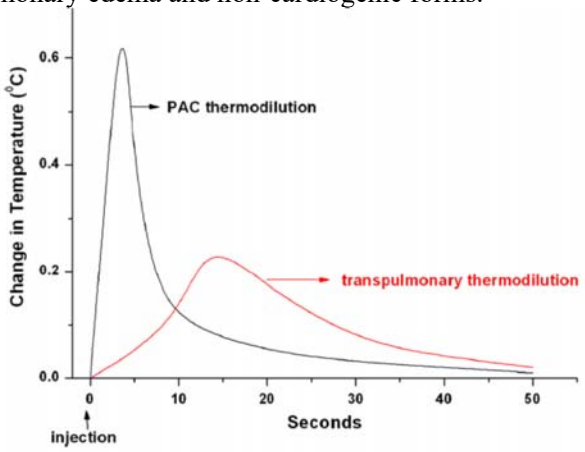

Figure 3. Comparison of transpulmonary thermodilution with PAC thermodilution showing the typical delay in peak temperature change

The information provided by PiCCO technology appears to correlate well compared to other methods. In a comparative study by Hadian et al, PiCCO and LiDCO systems performed adequately and comparably to each other and PAC, whereas FloTrac system proved inferior.[42] The preload estimation by GEDV might be more accurate than by pulmonary capillary wedge pressure.[43] In septic patients, owing to the periodical calibration, PiCCO can reliably detect CO changes induced by volume expansion and norepinephrine, in contrast to Flo/Trac. [44] In terms of clinical outcomes, Mutoh et al showed improvement in patients with subarachnoidal hemorrhage when monitored with PiCCO compared to PAC, while Uchino et al failed to do so in a cohort of 331 critically ill patients. [45, 46]

Since continuous measurements rely on arterial waveform analysis, they are subject to the inherent limitations regarding the presence of IABP counter-pulsation, significant aortic regurgitation or arrhythmias. Moreover, the fact that PAC estimates CO of the right ventricle, whereas PiCCO and LiDCO that of the left ventricle, may produce discrepancies in cases of intracardiac and intrapulmonary shunts.

A novelty in the field of transpulmonary thermodilution is represented by the EV1000/VolumeView monitor which needs a central arterial catheter just like PiCCO and calculates EVLW and GEDV as well as a new variable named the global ejection fraction (GEF). In two recent trials, the new device performed at least as well as PiCCO and was superior in estimating GEDV. [47, 48]

Thoracic bioempedance

Heart beat sends a certain amount of blood in the aorta in every cardiac cycle and transthoracic direct current resistance is deemed to be related to this periodical variation in aortic volume. The commercially available devices apply a high frequency current across the thorax and compare the amplitude of this current to that of the returning signal, thereby measuring the differences in thoracic impedance. The rate of the change of impedance and the ventricular ejection time are measured, and SV is derived from a mathematical formula. Unfortunately, the results can be influenced by motion artifacts, electrical interference, cardiac arrhythmias, heart and lung pathologies (anatomical deformities, pulmonary edema, pleural and pericardial effusions, intracardiac shunts) and the method has been shown inaccurate in comparison to thermodilution, especially in critically ill patients. [49-51]

Bioreactance

An evolution of thoracic bioimpedance method, bioreactance systems (NICOM device) measure the phase shift in voltage across the thorax. The impedance of the thorax when an alternating current runs through it, consists of two components: a resistive impedance (due to the resistor properties of thorax) and a reactive impedance (due to the capacitor properties). The principle of function of bioreactance devices is the following: 4 sensors are attached to the ventral thoracic wall as depicted in **Fig**. 4. Each sensor carries 2 electrodes. The outer one applies alternating voltage of known frequency and the inner one records the voltage. The sensors on each side of the body are paired so that voltage is delivered between the outer electrodes of each side and recorded between the inner electrodes of the same side. The comparison of the two signals discloses to what extent a time delay, or phase shift, has occurred. The blood absorbs electrons causing a delay in the signal (phase shift), which is proportional to the volume of blood pumped to the aorta. This phase shift is then translated to flow (**Fig**. 5) and eventually to stroke volume, using the following mathematical equation:

$$SV = C \times VET \times d\Phi/dt_{max}.$$

Bioreactance has been shown reliable in CO measurements when compared with thermodilution, in various clinical settings including patients post-cardiac surgery and patients with pulmonary hypertension. [52,-54]

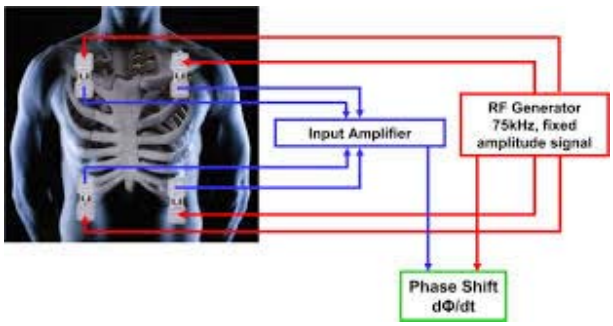

Figure 4. Bioreactance system sensor arrangement

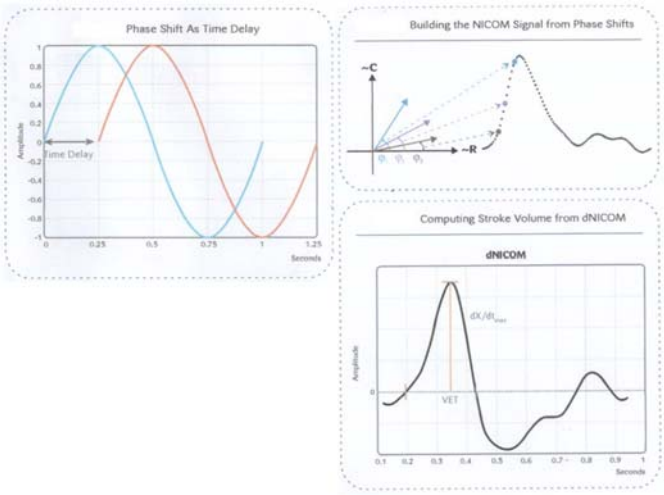

Figure 5. Stroke volume calculation from phase shift by bioreactance measuring system NICOM

Clinical implications

All the aforementioned methods aim at measuring SV and CO with acceptable accuracy, in order to provide a baseline estimation of the patient's cardiovascular status and detect differences induced by administration of small amounts of fluids or inotropic and vasoactive drugs, allowing guidance of therapy. The devices that use the pulse pressure analysis method for CO monitoring, also calculate stroke volume variation (SVV) and pulse pressure variation (PPV), as these variables fluctuate in response to intrathoracic pressure changes during respiratory phases in patients on positive pressure mechanical ventilation. There is general agreement that values of SVV >10% and PPV >13% indicate that the patient will probably respond to the administration of fluids, while lower values indicate the opposite. There are however significant limitations since the patient must be in mechanical ventilation with large tidal volumes (>8 ml/kg) and remain in sinus rhythm. [12]

In **conclusion**, there are no perfect methods to perform a less invasive hemodynamic monitoring but a number of technologies are now available to help the clinician. "Pulse

contour methods are based on solid physical principles, less solid physiological models, and involve substantial computations.'' [55] However, when periodically calibrated by thermodilution or indicator dilution, they provide reliable results and can indirectly calculate a variety of hemodynamic parameters that may prove useful in a clinical perspective. Nevertheless, there are still little data showing that any of these monitoring devices improve patient outcome and most importantly, physicians should not rely only on numerical information, but incorporate the patient's clinical, hemodynamic, laboratory and imaging data and integrate them all under their clinical judgement.

REFERENCES

1. 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* 2001; 345:1368-1377.
2. Marik PE, Cavallazzi R. Does the central venous pressure predict fluid responsiveness? An updated meta-analysis and a plea for some common sense. *Crit Care Med* 2013; 41:1774-1781.
3. Boyd JH, Forbes J, Nakada T, et al: Fluid resuscitation in septic shock: A positive fluid balance and elevated central venous pressure increase mortality. *Crit Care Med* 2011; 39:259-265.
4. Connors AF Jr, Speroff T, Dawson NV, et al. The effectiveness of right heart catheterization in the initial care of critically ill patients. SUPPORT Investigators. *JAMA* 1996; 276:889-897.
5. Valtier B, Cholley BP, Belot JP, e. Noninvasive monitoring of cardiac output in critically ill patients using transesophageal Doppler. *Am J Respir Crit Care Med* 1998; 158:77-83.
6. Marik PE. Noninvasive cardiac output monitors: a state-of the-art review. *J Cardiothorac Vasc Anesth* 2013;27:121-34.
7. Dark PM1, Singer M. The validity of trans-esophageal Doppler ultrasonography as a measure of cardiac output in critically ill adults. *Intensive Care Med* 2004; 30:2060-2066.
8. Sinclair S, James S, Singer M. Intraoperative intravascular volume optimisation and length of hospital stay after repair of proximal femoral fracture: randomised controlled trial. *BMJ* 1997; 315:909–912.
9. Venn R, Steele A, Richardson P, et al. Randomized controlled trial to investigate influence of the fluid challenge on duration of hospital stay and perioperative morbidity in patients with hip fractures. *Br J Anaesth* 2002; 88:65–71.
10. Noblett SE, Snowden CP, Shenton BK, Horgan AF. Randomized clinical trial assessing the effect of Doppler-optimized fluid management on outcome after elective colorectal resection. *Br J Surg* 2006; 93:1069–1076.
11. Muller L, Toumi M, Bousquet PJ, et al. An increase in aortic blood flow after an infusion of 100 ml colloid over 1 minute can predict fluid responsiveness: the mini-fluid challenge study. *Anesthesiology* 2011; 115:541–547.
12. Monnet X, Teboul JL. Assessment of volume responsiveness during mechanical ventilation: recent advances. *Crit Care* 2013;17:217.
13. Erlanger J, Hooker DR. An experimental study of blood pressure and of pulse-pressure in man. *Johns Hopkins Hosp Rep* 1904; 12:145–378.
14. Wesseling KH, de Wit B, Weber JAP, Ty SN. A simple device for the continuous measurement of cardiac output. *Adv Cardiovasc Phys* 1983; 5:16–52.
15. Chamos C, Vele L, Hamilton M, Cecconi M. Less invasive methods of advanced hemodynamic monitoring: principles, devices, and their role in the perioperative hemodynamic optimization. *Perioper Med (Lond)* 2013; 2:19.
16. Mayer J, Boldt J, Poland R, Peterson A, Manecke GR Jr. Continuous arterial pressure waveform-based cardiac output using the FloTrac/Vigileo: a review and meta-analysis. *J Cardiothorac Vasc Anesth* 2009; 23:401–406.
17. 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* 2011; 37:233-240.
18. 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* 2011; 106:776-784.
19. Takala J, Ruokonen E, Tenhunen JJ, Parviainen I, Jakob SM. Early noninvasive cardiac output monitoring in hemodynamically unstable intensive care patients: A multicenter randomized controlled trial. *Crit Care* 2011; 15:R148.
20. Ji F, Li J, Fleming N, Rose D, Liu H. Reliability of a new 4th generation FloTrac algorithm to track cardiac output changes in patients receiving phenylephrine. *J Clin Monit Comput* 2014 Sep 30. [Epub ahead of print]
21. Scolletta S, Romano SM, Biagioli B, et al. Pressure recording analytical method (PRAM) for measurement of cardiac output during various haemodynamic states. *Br J Anaesth* 2005; 95:159-165.
22. Franchi F, Silvestri R, Cubattoli L, et al. Comparison between an uncalibrated pulse contour method and thermodilution technique for cardiac output estimation in septic patients. *Br J Anaesth* 2011; 107:202-208.
23. Calamandrei M, Mirabile L, Muschetta S, et al. Assessment of cardiac output in children: A comparison between the pressure recording analytical method and Doppler echocardiography. *Pediatr Crit Care Med* 2008; 9:310-312.
24. Giomarelli P, Biagioli B, Scolletta S. Cardiac output monitoring by pressure recording analytical method in cardiac surgery. *Eur J Cardiothorac Surg* 2004; 26:515-520
25. Urbano J, López J, González R, et al. Measurement of cardiac output in children by pressure-recording analytical method. *Pediatr Cardiol* 2015; 36:358-364.
26. Donati A, Carsetti A, Tondi S, et al. Thermodilution vs pressure recording analytical method in hemodynamic stabilized patients. *J Crit Care* 2014; 29:260-264.
27. Saxena R, Durward A, Puppala NK, Murdoch IA, Tibby SM. Pressure recording analytical method for measuring cardiac

output in critically ill children: a validation study. *Br J Anaesth* 2013; 110:425-431.
28. Scolletta S, Miraldi F, Romano SM, Muzzi L. Continuous cardiac output monitoring with an uncalibrated pulse contour method in patients supported with mechanical pulsatile assist device. *Interact Cardiovasc Thorac Surg* 2011; 13:52-56.
29. Garisto C, Favia I, Ricci Z, et al. Pressure recording analytical method and bioreactance for stroke volume index monitoring during pediatric cardiac surgery. *Paediatr Anaesth* 2015; 25:143-149.
30. Fischer MO, Avram R, Cârjaliu I, et al. Non-invasive continuous arterial pressure and cardiac index monitoring with Nexfin after cardiac surgery. *Br J Anaesth* 2012; 109:514–521.
31. 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* 2012; 67:377–383.
32. van der Spoel A, Voogel AJ, Folkers A, Boer C, Bouwman RA. Comparison of noninvasive continuous arterial waveform analysis (Nexfin) with transthoracic Doppler echocardiography for monitoring of cardiac output. *J Clin Anesth* 2012; 24:304–309.
33. Chen G, Meng L, Alexander B, Tran NP, Kain ZN, Cannesson M. Comparison of noninvasive cardiac output measurements using the Nexfin monitoring device and the esophageal Doppler. *J Clin Anesth* 2012; 24:275–283.
34. Nowak RM, Nanayakkara P, DiSomma S, et al. Noninvasive hemodynamic monitoring in emergency patients with suspected heart failure, sepsis and stroke: the PREMIUM registry. *West J Emerg Med* 2014; 15:786-794.
35. Ameloot K, Van De Vijver K, Broch O, et al. Nexfin noninvasive continuous hemodynamic monitoring: validation against continuous pulse contour and intermittent transpulmonary thermodilution derived cardiac output in critically ill patients. *ScientificWorldJournal* 2013; 2013:519080.
36. Ameloot K, Van De Vijver K, Van Regenmortel N, et al. Validation study of Nexfin® continuous non-invasive blood pressure monitoring in critically ill adult patients. *Minerva Anestesiol* 2014; 80:1294-1301.
37. Mora B, Ince I, Birkenberg B, et al. Validation of cardiac output measurement with the LiDCO™ pulse contour system in patients with impaired left ventricular function after cardiac surgery. *Anaesthesia* 2011; 66:675–681.
38. Costa MG, Della Rocca G, Chiarandini P, et al. Continuous and intermittent cardiac output measurement in hyperdynamic conditions: pulmonary artery catheter vs lithium dilution technique. *Intensive Care Med* 2008; 34:257-263.
39. Oren-Grinberg A. The PiCCO monitor. *Int Anesthesiol Clin* 2010; 48:57-85.
40. Michard F, Alaya S, Zarka V, et al. Global end-diastolic volume as an indicator of cardiac preload in patients with septic shock. *Chest* 2003; 124:1900–1908.
41. 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 oedema: a prospective multicenter study on the quantitative differential diagnostic definition for acute lung injury/acute respiratory distress syndrome. *Crit Care* 2012; 16:R232.
42. Hadian M, Kim HK, Severyn DA, Pinsky MR. Cross-comparison of cardiac output trending accuracy of LiDCO, PiCCO, FloTrac and pulmonary artery catheters. *Crit Care* 2010; 14:R212.
43. Wiesenack C, Prasser C, Keyl C, Rödīg G. 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. *Cardiothorac Vasc Anesth* 2001; 15:584-588.
44. Monnet X, Anguel N, Naudin B, Jabot J, Richard C, Teboul JL. Arterial pressure-based cardiac output in septic patients: different accuracy of pulse contour and uncalibrated pressure waveform devices. *Crit Care* 2010; 14:R109.
45. Mutoh T, Kazumata K, Ishikawa T, et al: Performance of bedside transpulmonary thermodilution monitoring for goal-directed hemodynamic management after subarachnoid hemorrhage. *Stroke* 2009; 40:2368-2374.
46. Uchino S, Bellomo R, Morimatsu H, et al. Pulmonary artery catheter versus pulse contour analysis: a prospective epidemiological study. *Crit Care* 2006; 10:R174.
47. 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 2012; 16:R98.
48. 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* 2013; 111:573-579.
49. Marik PE, Pendelton JE, Smith R. A comparison of hemodynamic parameters derived from transthoracic electrical bioimpedance with those parameters obtained by thermodilution and ventricular angiography. *Crit Care Med* 1997; 25:1545-1550.
50. Kamath SA, Drazner MH, Tasissa G, et al. Correlation of impedance cardiography with invasive hemodynamic measurements in patients with advanced heart failure: The bioimpedance CardioGraphy (BIG) substudy of the ESCAPE trial. *Am Heart J* 2009; 158:217-223.
51. 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* 2009; 26:1067-1071.
52. Rich JD, Archer SL, Rich S. Evaluation of noninvasively measured cardiac output in patients with pulmonary hypertension. *Am J Respir Crit Care Med* 2011; 183:A6440.
53. Squara P, Denjean D, Estagnasie P, et al. Noninvasive cardiac output monitoring (NICOM): A clinical validation. *Intensive Care Med* 2007; 33:1191-1194.
54. Raval NY, Squara P, Cleman M, et al. Multicenter evaluation of noninvasive cardiac output measurement by bioreactance technique. *J Clin Monit Comput* 2008; 22:113-119.
55. Van Lieshout JJ, Wesseling KH. Continuous cardiac output by pulse contour analysis? *Br J Anaesth* 2001; 86:467–469.