Education-Family Physician Corner

An Evaluation of Contemporary Cardiac Output Monitors

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Cardiac output (CO) monitoring is an invaluable tool for management of critically ill patients in the intensive care units (ICU) and high-risk patients undergoing surgery.

Measurements of CO were not available until 1970, when Swan et al introduced the flow-directed balloon-tipped pulmonary artery catheter (PAC); this catheter is inserted at the bedside and is considered the gold standard for accurate CO measurements[1,2]. Recently, minimally invasive and non-invasive alternative CO monitors have emerged that not only overcome the PAC's invasive limitations, but are also able to guide fluid optimization, which has been shown to improve the outcome after major surgery[3].

This is a review of the characteristics of the PAC and compares it with other less invasive and non-invasive CO monitors currently available.

We will look at issues of accuracy, dependability, complications, limitations to use, the ability to give continuous readings and how these monitoring systems could be used to guide fluid status optimization.

The systems we will review include the following:

- **Pulmonary artery catheter (as the gold standard)**
- **LiDCO Plus™ (LiDCO Ltd, London, UK)**
- **LiDCO Rapid™ (LiDCO Ltd, London, UK)**
- **PiCCO Plus™ (Pulsion Medical Systems, Munich, Germany)**
- **The Edwards FloTrac™ sensor/Vigileo™ monitor (Edwards Lifesciences, Irvine, USA)**
- **Oesophageal Doppler Ultrasound**
- **Finometer™ (Finapres Medical Systems, Amsterdam, Netherlands)**
- **Nexfin™ (Bmeye B.V., Amsterdam, Netherlands)**

The PAC involves introducing a balloon-tipped catheter into the superior vena cava through one of the central veins, through the right side of the heart and into the pulmonary circulation. Inflation of the balloon would allow the catheter to float in the pulmonary circulation until it wedges in a distal branch of the pulmonary artery. Pulmonary capillary wedge pressure (PCWP) is then measured at the catheter tip. In addition, it could provide intermittent, accurate estimates of the central venous pressure (CVP), right-sided intracardiac pressures, pulmonary artery pressure (PAP), CO, systemic vascular resistance (SVR) and pulmonary vascular resistance (PVR). These indices are measured by using the Fick's principle, which measures CO by the intermittent thermo dilution technique. The Fick's principle implies that when a certain amount of indicator is injected into an afferent vessel, and its concentration is measured downstream in the efferent vessel, the CO could be obtained by calculating the decay in concentration over time[4].

Since it was the first modality to measure the CO accurately, it gained immense popularity among anesthetists and intensivists. It was used as a diagnostic tool in critically ill patients, such as for differentiating between cardiogenic and non-cardiogenic pulmonary edema, evaluating pulmonary artery hypertension (PAH), atrial septal defects (ASD), ventricular septal defects (VSD), mitral regurgitation, cardiac tamponade and restrictive cardiomyopathy (RCM). In addition, it was found to be helpful in guiding fluid infusions, inotropes and vasopressor therapies in shock, heart failure, renal failure and cardiac surgery patients[4,5].

However, with increased use, various complications, such as thromboembolism, pulmonary valvular endocarditis, air embolism, pulmonary hemorrhage, pulmonary infarction and distal pulmonary artery rupture were recognized[4,6-8]. In recent years, its usefulness has been questioned as many trials have shown conflicting results regarding both benefit and mortality[9-15].

With the availability of less invasive hemodynamic monitoring tools, its use has significantly declined and is mostly limited to diagnosis and perioperative management of patients with PAH and intracardiac shunts[16].

LiDCO Plus™ (LiDCO Ltd, London, UK)

The LiDCO Plus™ requires the insertion of an arterial line and a peripheral/central venous line.

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It is a continuous CO monitor utilizing the lithium indicator dilution cardiac output (LiDCO™), and the pulse CO realtime technology (Pulse CO™).

The LiDCO™ measures the CO intermittently and accurately by using the indicator dilution technique, where intravenous lithium acts as the indicator (using the Fick's principle as in PAC).

The Pulse CO™ measures mean arterial pressure (MAP), systolic blood pressure (SBP), diastolic blood pressure (DBP), heart rate (HR), stroke volume (SV) and CO continuously on beat-by-beat by analyzing the whole arterial waveform. It also has the advantage of monitoring the preload responsiveness parameters including the stroke volume variation (SVV) and the pulse pressure variation (PPV)[17].

The CO measurements generated by the LiDCO™ component are used to calibrate the CO measurements obtained by the Pulse CO™ once every 8 hours. After calibration, the Pulse CO™ would provide a reliable, continuous beat-by-beat CO measurement. It is widely validated for its accuracy regarding CO monitoring[17-22].

However, LiDCO Plus™ could not be used in patients weighing < 40 kg, pregnant and those on oral lithium medications. Its measurements are unreliable in patients receiving muscle relaxant infusions[23,24]. It is time-consuming, and staff would require training in order to perform the calibration.

LiDCO Rapid™ (LiDCO Ltd, London, UK)

The LiDCO Rapid™ is a new monitor technically identical to the Pulse CO™ component of the LiDCO Plus™ monitor, only requiring the insertion of an arterial line. The LiDCO Rapid™ is compact, easily applied and does not require lithium calibration; therefore, it avoids the limitations of LiDCO Plus™. This device does not provide absolute estimates of the CO; however, it tracks the trend of change in flow and resistance, thus, providing continuous monitoring of the BP, HR, SV, CO and also preload responsiveness parameters (SVV and PPV).

PiCCO Plus™ (Pulsion Medical Systems, Munich, Germany)

This technology is similar in principle to the LiDCO Plus™. It requires the insertion of an arterial line and a central line. The PiCCO Plus™ involves two separate components: the Stewart-Hamilton principle intermittent transpulmonary thermodilution (TPTD) technique and the pulse contour analysis.

The TPTD technique is used intermittently to obtain accurate estimates of the CO. Cold saline is injected into the superior vena cava via a central venous line, and the change in temperature downstream is measured in the femoral artery via a femoral arterial catheter.

The CO measurements generated by the TPTD component are used to calibrate the CO measurements obtained by the pulse contour once every 8 hours. After calibration, the pulse contour would provide a reliable continuous beat-by-beat CO measurement. The PiCCO Plus™ is widely validated for its accuracy[25].

In addition to the parameters assessed by the LiDCO Plus™, the PiCCO Plus™ measures the cardiac function index (CFI), global end-diastolic volume (GEDV), Global ejection fraction (GEF), intra-thoracic blood volume (ITBV) and extra-vascular lung water (EVLW). These parameters could help the clinician at the bedside to determine whether the pulmonary edema is of cardiogenic origin or not, the volume of blood in the cardiac chambers (which reflects the volume status of the patient) and the amount of pulmonary edema fluid[26-28].

Edwards FloTrac™ sensor and Vigileo™ monitor (Edwards LifeSciences, Irvine, USA)

This is a minimally invasive, reliable, continuous CO monitoring device which requires only a peripheral arterial line (PAL). It provides accurate measurements of CO, without the necessity of calibrating against other CO monitoring techniques. The FloTrac™ sensor is connected to the patient's PAL. The Vigileo™ monitor processes arterial signals obtained from the FloTrac™ sensor to generate an accurate estimate of the CO, SV and SVV that are displayed at 20-second intervals. In addition, connecting the monitor to a central venous catheter could provide estimates of the SVR[29,30]. Limitations to its use include the presence of aortic regurgitation or irregular pulse. In addition, a ventricular assist device or an intra-aortic balloon pump (IABP) may affect the accuracy of the FloTrac™ readings[2,31].

Esophageal Doppler Ultrasound

A flexible probe containing a Doppler ultrasound in its tip is inserted orally into the esophagus and is positioned at the mid-thoracic level. It measures the flow of blood in the descending aorta and estimates the CO by multiplying the velocity of the blood flow with the cross-sectional area of the aorta. It measures the SV, CO and SVR[32-34].

Finometer™ (Finapres Medical Systems, Amsterdam, Netherlands)

The Finometer™ is a non-invasive, beat-by-beat hemodynamic monitor that generates a continuous pulse waveform using a finger cuff, which is then computed to provide continuous blood pressure and CO measurements. The continuous BP measurements are further calibrated against the brachial arterial pressure[35-40].

This device is accurate regarding BP monitoring and tracking the trends of change in CO. It could not be used in conditions associated with hypoperfusion of the extremities and in patients below six years of age[41-46].

Nexfin™ (BMEYE B.V, Amsterdam, Netherlands)

The Nexfin™ is similar in principle to the Finometer™. It also measures the hemodynamics continuously through a finger cuff with a similar level of accuracy[47]. The Nexfin™, compared to the Finometer™, is smaller in size and takes less time to operate. It also does not require physical calibration against the brachial arterial pressure. A built-in computational algorithm is used for the purpose. A summary of the different methods of calculating CO could be seen in table 1.

Table 1: Comparison of Hemodynamic Monitoring Techniques

Technology	Invasiveness*	Principle	Major Parameters Measured	Advantages	Disadvantages	Reliability	Proposed Area of Use
Pulmonary Artery Catheter	3	Thermodilution	CVP, PCWP, CO, SVR	Measures PCWP	Invasive, Complications, Requires expertise	Validated for Accuracy	Cardiac surgery, Contraindications for less invasive modalities
LiDCO Plus™	2	Calibrated Pulse waveform analysis	CVP, CO, SVR, SVV, PPV	Accuracy	Lithium injection, Pregnancy, Lithium therapy, Muscle relaxant infusions, Weight < 40 kg, Does not measure intrathoracic volume indices	Validated for Accuracy	Routine hemodynamic monitoring, Shock
LiDCO Rapid™	1	Uncelebrated Pulse waveform analysis	CO, SVV, PPV	Lithium not required, Trend Monitor	Inaccurate	Follows the trends of change in CO	Routine hemodynamic monitoring, Goal-directed fluid management
PiCCO Plus™	2	Calibrated Pulse waveform analysis	CVP, CO, SVR, SVV, PPV GEDV, EVLW, PVPI, CFI, GEF	Accuracy, Measures Intrathoracic volume indices	Invasive, Unreliable in arrhythmias	Validated for Accuracy	Routine invasive hemodynamic monitoring Multifactorial shock, Quantify pulmonary edema
Edwards FloTrac™/ Vigileo™	1	Uncelebrated Pulse waveform analysis	CO, SVV, PPV	Built in calibration, Acceptable accuracy	Does not measure intrathoracic volume indices	Validated for Accuracy	Routine hemodynamic monitoring, Shock
Oesophageal Doppler	1	Doppler Ultrasound	CO, SVV	Accuracy, Does not require invasive lines	Training required, Limited parameters?	Validated for Accuracy	Routine hemodynamic monitoring, Goal-directed fluid management
Finometer™	0	Uncelebrated Pulse waveform analysis	BP, CO, SVR	Rapid assembly, Easy to use, No invasive lines	Requires brachial arterial pressure calibration, Not reliable in shock or arrhythmias (limited utility in ICU)	Follows the trends of change in CO	Perioperative hemodynamic monitoring
Nexfin™	0	Uncelebrated Pulse waveform analysis	BP; CO; SVR	Rapid assembly, Easy to use, Does not require invasive lines, Compact machine, Brachial arterial pressure calibration not required	Not reliable in shock or arrhythmias (limited utility in ICU)	Follows the trends of change in CO	Perioperative hemodynamic monitoring

BP: blood pressure
CO: cardiac output
SVV: stroke volume variation
CVP: central venous pressure
CFI: cardiac function arrest
GEF: global ejection fraction
GEDV: global end-diastolic volume
PPV: pulse pressure variation
EVLW: extravascular lung water
SVR: systemic vascular resistance
PCWP: pulmonary capillary wedge pressure
PVPI: pulmonary vascular permeability index
* **0**: noninvasive; **1**: minimally invasive; **2**: invasive; **3**: highly invasive

CONCLUSION

A variety of CO monitors exists with different features regarding the degree of invasiveness, accuracy, limitations, range of hemodynamic variables provided and the ability to guide for fluid optimization.

CO monitoring with a PAC should be kept as a last resort because it is highly invasive. PiCCO Plus™, LiDCO Plus™ and the Edwards FloTrac™/Vigileo™ systems are suitable, less invasive alternatives that provide accurate estimates of the CO. LiDCO Rapid™ is a trend CO monitor (tracks the trend of change in CO values) that in contrast with the LiDCO Plus™, saves the hassle of lithium calibration and could be used for fluid optimization guiding. Non-invasive finger arterial CO monitoring using Nexfin™ or Finometer™ devices could provide reliable trend CO monitoring by just using a finger cuff in non-shocked states.

Up to date, there is no such thing as an ideal monitor that could be employed in all clinical scenarios. The choice of a monitor should be tailored upon availability and the patient's condition.

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REFERENCES

1. Swan HJ, Ganz W, Forrester J, et al. Catheterization of the Heart in Man with use of a Flow-Directed Balloon-Tipped Catheter. N Engl J Med 1970; 283(9):447-51.
2. Maus TM, Lee DE. Arterial Pressure-Based Cardiac Output Assessment. J Cardiothorac Vasc Anesth 2008; 22(3):468-73.
3. Benes J, Chytra I, Altmann P, et al. Intraoperative Fluid Optimization Using Stroke Volume Variation in High Risk Surgical Patients: Results of Prospective Randomized Study. Crit Care 2010; 14(3):R118.
4. Summerhill EM, Baram M. Principles of Pulmonary Artery Catheterization in the Critically Ill. Lung 2005; 183(3):209-19.
5. Sandham JD, Hull RD, Brant RF, et al. A Randomized, Controlled Trial of the Use of Pulmonary-Artery Catheters in High-Risk Surgical Patients. N Engl J Med 2003; 348(1):5-14.
6. Hoar PF, Wilson RM, Mangano DT, et al. Heparin Bonding Reduces Thrombogenicity of Pulmonary-Artery Catheters. N Engl J Med 1981; 305(17):993-5.
7. Mermel LA, Maki DG. Infectious Complications of Swan-Ganz Pulmonary Artery Catheters. Pathogenesis, Epidemiology, Prevention, and Management. Am J Respir Crit Care Med 1994; 149(4 Pt 1):1020-36.
8. Heckmann JG, Lang CJ, Kindler K, et al. Neurologic Manifestations of Cerebral Air Embolism as a Complication of Central Venous Catheterization. Crit Care Med 2000; 28(5):1621-5.
9. Rhodes A, Cusack RJ, Newman PJ, et al. A Randomised, Controlled Trial of the Pulmonary Artery Catheter in Critically Ill Patients. Intensive Care Med 2002; 28(3):256-64.
10. Richard C, Warszawski J, Anguel N, et al. Early Use of the Pulmonary Artery Catheter and Outcomes in Patients with Shock and Acute Respiratory Distress Syndrome: A Randomized Controlled Trial. JAMA 2003; 290(20):2713-20.
11. Harvey S, Harrison DA, Singer M, et al. Assessment of the Clinical Effectiveness of Pulmonary Artery Catheters in Management of Patients in Intensive Care (PAC-Man): A Randomised Controlled Trial. Lancet 2005; 366(9484):472-7.
12. Binanay C, Califf RM, Hasselblad V, et al. Evaluation Study of Congestive Heart Failure and Pulmonary Artery Catheterization Effectiveness: The ESCAPE Trial. JAMA 2005; 294(13):1625-33.
13. 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(11):889-97.
14. Peters SG, Afessa B, Decker PA, et al. Increased Risk Associated with Pulmonary Artery Catheterization in the Medical Intensive Care Unit. J Crit Care 2003; 18(3):166-71.
15. Shah MR, Hasselblad V, Stevenson LW, et al. Impact of the Pulmonary Artery Catheter in Critically Ill Patients: Meta-Analysis of Randomized Clinical Trials. JAMA 2005; 294(13):1664-70.
16. Marik PE. Obituary: Pulmonary Artery Catheter 1970 to 2013. Ann Intensive Care 2013; 3(1):38.
17. Linton NW, Linton RA. Estimation of Changes in Cardiac Output from the Arterial Blood Pressure Waveform in the Upper Limb. Br J Anaesth 2001; 86(4):486-96.
18. Kurita T, Morita K, Kato S, et al. Comparison of the Accuracy of the Lithium Dilution Technique with the Thermodilution Technique for Measurement of Cardiac Output. Br J Anaesth 1997; 79(6):770-5.
19. Linton R, Band D, O'Brien T, et al. Lithium Dilution Cardiac Output Measurement: A Comparison with Thermodilution. Crit Care Med 1997; 25(11):1796-800.
20. Pittman J, Bar-Yosef S, SumPing J, et al. Continuous Cardiac Output Monitoring with Pulse Contour Analysis: A Comparison with Lithium Indicator Dilution Cardiac Output Measurement. Crit Care Med 2005; 33(9):2015-21.
21. 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 2007; 62(8):760-8.
22. Missant C, Rex S, Wouters PF. Accuracy of Cardiac Output Measurements with Pulse Contour Analysis (PulseCO) and Doppler Echocardiography During Off-Pump Coronary Artery Bypass Grafting. Eur J Anaesthesiol 2008; 25(3):243-8.
23. Pearse RM, Ikram K, Barry J. Equipment Review: An Appraisal of the Lidco Plus Method of Measuring Cardiac Output. Crit Care 2004; 8(3):190-5.
24. Jonas MM, Tanser SJ. Lithium Dilution Measurement of Cardiac Output and Arterial Pulse Waveform Analysis: An Indicator Dilution Calibrated Beat-by-Beat System for Continuous Estimation of Cardiac Output. Curr Opin Crit Care 2002; 8(3):257-61.
25. Sakka SG, Rühl CC, Pfeiffer UJ, et al. Assessment of Cardiac Preload and Extravascular Lung Water by Single Transpulmonary Thermodilution. Intensive Care Med 2000; 26(2):180-7.
26. Isakow W, Schuster DP. Extravascular Lung Water Measurements and Hemodynamic Monitoring in the Critically Ill: Bedside Alternatives to the Pulmonary Artery Catheter. Am J Physiol Lung Cell Mol Physiol 2006; 291(6):L1118-31.
27. Pohl T, Kozieras J, Sakka SG. Influence of Extravascular Lung Water on Transpulmonary Thermodilution-Derived Cardiac Output Measurement. Intensive Care Med 2008; 34(3):533-7.
28. Monnet X, Anguel N, Osman D, et al. Assessing Pulmonary Permeability by Transpulmonary Thermodilution Allows Differentiation of Hydrostatic Pulmonary Edema from ALI/ARDS. Intensive Care Med 2007; 33(3):448-53.
29. Manecke GR Jr, Auger WR. Cardiac Output Determination from the Arterial Pressure Wave: Clinical Testing of a Novel Algorithm that does not Require Calibration. J Cardiothorac Vasc Anesth 2007; 21(1):3-7.

30. McGee W, Horswell J, Janvier G. Validation of a Continuous Cardiac Output Measurement using Arterial Pressure Waveforms. Crit Care 2005; 9(Suppl 1):P62.
31. Manecke GR. Edwards FloTrac Sensor and Vigileo Monitor: Easy, Accurate, Reliable Cardiac Output Assessment using the Arterial Pulse Wave. Expert Rev Med Devices 2005; 2(5):523-7.
32. Berton C, Cholley B. Equipment Review: New Techniques for Cardiac Output Measurement--Oesophageal Doppler, Fick Principle using Carbon Dioxide, and Pulse Contour Analysis. Crit Care 2002; 6(3):216-21.
33. Alhashemi JA, Cecconi M, Hofer CK. Cardiac Output Monitoring: An Integrative Perspective. Crit Care 2011; 15(2):214.
34. King SL, Lim MS. The use of the Oesophageal Doppler Monitor in the Intensive Care Unit. Crit Care Resusc 2004; 6(2):113-22.
35. Penaz J. Photoelectric Measurement of Blood Pressure, Volume and Flow in the Finger. In: Albert A, Vogt W, Hellig W, eds. Digest of the 10th International Conference on Medical and Biological Engineering. Dresden: International Federation for Medical and Biological Engineering, 1973: 104.
36. Wesseling KH, De Witt B, van der Hoeven GMA, et al. Physiocal, Calibrating Finger Vascular Physiology for Finapres. Homeostasis 1995; 36:67-82.
37. Wesseling KH, DeWitt B, Weber JAP, et al. A Simple Device for the Continuous Measurement of Cardiac Output: Its Model Basis and Experimental Verification. Adv Cardiovasc Phys 1983; 5:16-52.
38. Jansen JR, Wesseling KH, Settels JJ, et al. Continuous Cardiac Output Monitoring by Pulse Contour during Cardiac Surgery. Eur Heart J 1990; 11 Suppl I:26-32.
39. Bos WJ, van Goudoever J, van Montfrans GA, et al. Reconstruction of Brachial Artery Pressure from Noninvasive Finger Pressure Measurements. Circulation 1996; 94(8):1870-5.
40. Gizdulich P, Imholz BP, van den Meiracker AH, et al. Finapres Tracking of Systolic Pressure and Baroreflex Sensitivity Improved by Waveform Filtering. J Hypertens 1996; 14(2):243-50.
41. Schutte AE, Huisman HW, van Rooyen JM, et al. Validation of the Finometer Device for Measurement of Blood Pressure in Black Women. J Hum Hypertens 2004; 18(2):79-84.
42. Hehenkamp WJ, Rang S, van Goudoever J, et al. Comparison of Portapres with Standard Sphygmomanometry in Pregnancy. Hypertens Pregnancy 2002; 21(1):65-76.
43. Guelen I, Westerhof BE, van der Sar GL, et al. Finometer, Finger Pressure Measurements with the Possibility to Reconstruct Brachial Pressure. Blood Press Monit 2003; 8(1):27-30.
44. Azabji Kenfack M, Lador F, Licker M, et al. Cardiac Output by Modelflow Method from Intra-Arterial and Fingertip Pulse Pressure Profiles. Clin Sci (Lond) 2004; 106(4):365-9.
45. Stok WJ, Baisch F, Hillebrecht A, et al. Noninvasive Cardiac Output Measurement by Arterial Pulse Analysis Compared with Inert Gas Rebreathing. J Appl Physiol (1985) 1993; 74(6):2687-93.
46. Wesseling KH, Settels JJ, van der Hoeven GM, et al. Effects of Peripheral Vasoconstriction on the Measurement of Blood Pressure in a Finger. Cardiovasc Res 1985; 19(3):139-45.
47. Eeftinck Schattenkerk DW, van Lieshout JJ, van den Meiracker AH, et al. Nexfin Noninvasive Continuous Blood Pressure Validated against Riva-Rocci/Korotkoff. Am J Hypertens 2009; 22(4):378-83.