MEDWIN PUBLISHERS
Committed to Create Value for Researchers

Anaesthesia & Critical Care Medicine Journal
ISSN: 2577-4301

Evolution of Perioperative Hemodynamic Monitoring from the Hand on Pulse to Hypotension Prediction Index

Shiraboina M[1], Ayya SS[2]*, Garre S[2], Anna AC[2], , Gajagouni N[1], Shashikanth T[3] and Ramachandran G[4]

[1]Department of Anaesthesiology, Gandhi Medical College, India
[2]Department of Anesthesiology, All India Institute of Medical Sciences, India
[3]Department of Anaesthesiology, Osmania Medical College, India
[4]Department of Anaesthesiology, ESIC Medical College, India

Review Article
Volume 10 Issue 1
Received Date: December 23, 2024
Published Date: January 16, 2025
DOI: 10.23880/accmj-16000250

***Corresponding author:** Syama Sundar Ayya, MD, DM (Cardiothoracic Anesthesiology), Additional Professor, Department of Anesthesiology, All India Institute of Medical Sciences, Bibinagar, Hyderabad, Telangana, India, Tel: 8179309677; Email: sasyasyama@gmail.com

Abstract

This manuscript describes the evolution of hemodynamic monitoring from simple manual methods to artificial intelligence-integrated monitoring and prediction systems. Manual methods, like palpation of peripheral pulse, capillary refill time and auscultation are simple and crucial in detecting hemodynamic changes during surgery. However, these methods are time consuming, difficult to monitor continuously and have limited reliability in critical situations like hypotension or hypothermia. Over time, advances in technology have improved perioperative monitoring through the invention of various non-invasive monitors like electrocardiogram, pulse oximetry, oscillometric blood pressure measurement, capnography, echocardiography, tissue oximetry, etc. and invasive monitors to measure arterial pressures, venous pressures and cardiac output. These monitors have improved the accuracy of hemodynamic measurements and fluid management in critically ill patients. Recently, there has been a growing emphasis on non-invasive or minimally invasive monitoring approaches, which have fewer complications than invasive techniques. However, most of these techniques show limited accuracy during major surgeries involving major hemodynamic changes and in critically ill patients. Monitors incorporating artificial intelligence (AI)-based tools, such as the hypotension prediction index (HPI), automated echocardiographic measurements (AEM), etc., have been demonstrated to be effective in making quick and accurate diagnoses as well as in predicting perioperative complications.

Keywords: Hand on Pulse; Hypotension; Hemodynamic Monitoring; Artificial Intelligence

Abbreviations

AI: Artificial Intelligence; HPI: Hypotension Prediction Index; AEM: Automated Echocardiographic Measurements; CVP: Central Venous Pressure; PAOP: Pulmonary Arterial Occlusion Pressure; SVV: Stroke Volume Variation; PPV: Pulse Pressure Variation; PVI: Pleth Variability Index; CO: Cardiac Output; ASA: American Society of Anaesthesiologists.

Introduction

The progression of haemodynamic monitoring from manual methods to artificial intelligence (AI) integrated prediction and measurements is a fascinating journey to improve perioperative patient safety and surgical outcomes. Static hemodynamic parameters such as central venous pressure (CVP), pulmonary arterial occlusion pressure (PAOP), etc. and dynamic variables, such as stroke volume variation (SVV), pulse pressure variation (PPV), and pleth variability index (PVI), are essential for the accurate diagnosis of hemodynamic disturbances, selection of appropriate interventions and assessing the effectiveness of the interventions. The main goal of hemodynamic monitoring is to evaluate tissue perfusion adequacy. Tissue perfusion is primarily influenced by perfusion pressure and cardiac output (CO), with deficiencies in either potentially leading to inadequate tissue perfusion and multi-organ failure. Monitoring these factors is crucial for enhancing perioperative outcomes and preventing complications related to hemodynamics.

The goals of hemodynamic monitoring are:

- Assess tissue perfusion adequacy.
- Identify the cause of inadequate perfusion.
- Initiate appropriate therapy.
- Titrate therapy to specific hemodynamic targets.

The advantages and disadvantages of various monitoring techniques are highlighted to improve the understanding of these devices and their role in the perioperative period.

Pulse Palpation, Cardiac Auscultation and Blood Pressure Monitoring

Deaths following chloroform anaesthesia emphasised the need to monitor vital signs like pulse, breathing and skin colour in the early days of anaesthesia. In the beginning, there was more emphasis on respiratory monitoring than feeling the pulse. Dr. Joseph Lister, M.D., a 19th-century British surgeon, criticized the practice of palpating the pulse, calling it “a most serious mistake” [1]. He argued that the safety of the patient would be better ensured by completely disregarding it, allowing the focus to be directed solely on the patient’s breathing.

Dr Edward Lawrie, a Scottish surgeon who led the Hyderabad chloroform commissions in 1888 and 1889, believed that feeling the pulse was unnecessary and the entire attention has to be devoted to respiration, as failure of the pulse is a late sign of improper administration or overdose of chloroform [2,3]. He proposed that the cessation or pause of respiration is one of the early signs of danger and should be addressed immediately by removing the chloroform mask and fresh air must be given.

In 1864, Dr Clover JT [4], a leading anaesthetist working on chloroform fatalities, advised that the pulse should be continuously monitored during anaesthesia and that any pulse irregularities should alert the anaesthetist to discontinue the anaesthetic [4].

The advent of the stethoscope marked a significant milestone in the history of medicine. It enabled routine and continuous monitoring of cardiac and respiratory sounds throughout the surgical procedures. This provided valuable insights into a patient’s cardiovascular and respiratory status, allowing for early detection of complications, which gave momentum for the widespread use of intraoperative auscultation. Dr. Robert Kirk used a stethoscope extended with Indian rubber tubing in 1896 to record the heart sound auscultation in the operating room [5]. Dr. Charles K. Teter emphasized the benefits of a precordial stethoscope during anaesthesia, particularly for high-risk individuals [6]. Dr Harvey Cushing strongly advocated the regular and uninterrupted monitoring of cardiac and respiratory sounds during anaesthesia [7].

Dr. Solis-Cohen introduced an oesophageal stethoscope for diagnostic purposes in 1893 [8]. After 1900, accurate blood pressure measurements became possible due to von Recklinghausen’s recommendation of a cuff and Korotkoff’s research on blood flow sounds beyond a deflating cuff [9,10]. Von Recklinghausen introduced a partially automated oscillotonometer in 1931 to measure blood pressure Von R [11]. These three basic monitoring methods-finger on the pulse, auscultation of heart sounds by stethoscope and NIBP estimation -are time-tested, standard techniques for hemodynamic monitoring during anaesthesia. They allow for a rough estimation of volume status, blood pressure, cardiac rhythm, and CO. However, their limitations include difficulty in continuous monitoring and potential inaccuracy in patients with atherosclerosis, peripheral arterial disease, severe hypotension, or hypothermia.

Single Channel ECG Monitoring

In 1922, Lennox, Graves RC and Levine SA [12] conducted the first prospective study using an intermittent electrocardiograph (ECG) to monitor patients in the operating room. Subsequent studies have shown the significance of utilizing ECG during surgery to detect arrhythmias [13-15]. In 1952, Himmelstein and Scheiner developed a cardiotachoscope that enabled the continuous display of ECG [16]. Later, several studies described the various arrhythmias that could occur during anaesthesia [17-20].

Pulse Oximetry

The first portable pulse oximeter was created in 1942 by British scientist Glen Millikan to monitor oxygen saturation of pilots while they were in the air. Japanese bioengineer Takuo Aoyagi used the ratio of red to infrared light absorption in arterial blood to produce conventional pulse oximetry in 1972.

In 1984, Dr. Cooper recommended the use of pulse oximetry monitoring to identify hypoxia and enhance perioperative outcomes [21]. Subsequently, Pulse oximetry was recognized as a standard of care by the American Society of Anaesthesiologists (ASA).

Invasive Blood Pressure Monitoring

Stephen Hales did the first invasive blood pressure measurement in the eighteenth century [22]. In 1949, the first clinically relevant invasive arterial catheter placement was accomplished by Peterson and colleagues, who described it as: "A small plastic catheter, inserted into an artery through a needle, is left in the artery when the needle is withdrawn. Attached to a capacitance manometer, this technique permits recording for long periods without discomfort and allows relatively free mobility of the subject" [23]. Since then, Peirce EC [24] and Seldinger SI [25] have both provided descriptions of multiple techniques. Later, the wide medical application of polytetrafluoroethylene made percutaneous access more convenient, leading to easier placement of percutaneous cannula for continuous monitoring of arterial blood pressure. The concurrent advancements in pressure transducers, continuous flush systems, and cost-effectiveness greatly contributed to the widespread use of invasive arterial monitoring. In 1930, Klein O [26] described catheterizations of the right side of the heart and the use of Fick's principle to assess CO. The importance of pulmonary artery wedge pressure in determining left atrial pressure was described by Dexter L [27] and Werko L [28] in 1947.

In 1970, Swan H and Ganz W [29] introduced a balloon-tipped flow-guided catheter technique for estimating pulmonary arterial wedge pressure. This modification helped use this catheter in operating rooms, intensive care units, and catheterization laboratories. Pulmonary artery catheters (PAC) evolved from a device that enabled intermittent CO measurements in combination with static pressures to a monitoring tool that provides continuous data on estimating CO, oxygen supply-and-demand balance, cardiac chamber filling pressures, pulmonary vascular resistance, etc.

The complexity of interpreting measurements, along with the invasiveness and potential complications, has restricted invasive monitoring to high-risk surgical and critically ill patients. Advances in non-invasive or minimally invasive techniques for evaluating cardiac output have further restricted its potential use Shah MR [30].

Dynamic Hemodynamic Monitoring

Over the past twenty years, research has increasingly focused on using dynamic measurements to determine the cause of hemodynamic instability and fluid responsiveness. This shift was driven by the observation that only 50% of patients show a positive response to fluid administration and the subsequent increase in mortality rates associated with fluid overload [31,32]. Recent advancements in pulse oximetry include the incorporation of dynamic variables like the pulse variability index and pleth variability index. The pulse variability index reflects fluctuations in arterial pulse amplitude while the pleth variability index gauges changes in the plethysmography waveform in response to respiration. Both measures are valuable tools for assessing intravascular volume status, fluid responsiveness and guiding goal-directed therapy. However, their non-invasive nature, sensitivity to rapid shifts in vascular tone and localized factors can reduce their accuracy, particularly in critically ill patients and those on vasopressor support.

Various invasive and minimally invasive techniques now assess fluid responsiveness using dynamic indices such as pulse pressure variation (PPV), stroke volume variation (SVV), and real-time response of stroke volume to passive leg raising (PLR) or end-expiration occlusion [33]. Numerous clinical studies have since demonstrated the superiority of the invasive functional hemodynamic variables over static preload measures [33-36]. Consequently, measuring CO response to fluid administration through arterial pulse contour analysis has also gained traction.

Pulse Contour Analysis

Erlanger and Hooker, in 1904, suggested that CO was proportional to arterial pulse pressure [37]. Pulse contour devices work on the same principle and relate the contour of the arterial pressure waveform to stroke volume and systemic vascular resistance. An algorithm is used to determine the CO. PiCCO, VolumeView, LiDCO, and FloTrac/Vigileo utilize this principle to derive CO. PiCCO calculates CO using the Stewart-Hamilton equation by measuring temperature differences and producing a dissipation curve. Thermo dilution-derived CO measurements are used to calibrate the system [38].

The LiDCO monitor (LiDCO, Cambridge, UK) utilizes a bolus indicator dilution technique to measure the initial CO and calibrate the software. It uses the pulse power rather than pulse contour to estimate the stroke volume [39]. The LiDCO device

has the advantage that only a standard arterial line is required.

The FloTrac/Vigileo system (Edwards Lifesciences, Irvine, CA, USA) also utilizes a blood flow sensor attached to a standard arterial catheter. A newly improved algorithm is used to calculate CO every 20 seconds. Stroke volume is calculated by multiplying arterial pulsatility and a constant (K) derived from the patient's specific vascular compliance. This stroke volume is then multiplied by heart rate to calculate CO. Unlike other pulse contour devices, the FloTrac/Vigileo does not require external calibration [40].

Oesophageal Doppler

A flexible probe with a Doppler transducer at the tip is inserted into the oesophagus through the nose or mouth [41]. The probe tip, usually placed at T5 or T6 vertebrae will measure the blood flow velocity in the descending aorta. The stroke volume is calculated from the measured stroke distance and the nomogram, which is a calibrated constant that estimates the diameter of the aorta. The main drawback of this method is that 30% of the blood leaves the aorta before the point of measurement. Different companies offer various solutions to overcome this [42]. Although it showed good correlation in normal subjects, a high degree of bias and poor correlation were observed in patients with aortic valve pathologies and low CO states. This method is not recommended for patients with severe bleeding disorders or oesophageal disorders [43-46].

Non-Invasive Cardiac Output Monitoring

Invasive monitoring methods using pulmonary artery catheters, oesophageal probes, or arterial catheters are usually associated with complications. Conversely, non-invasive methods provide a safer alternative, although their reliability can be limited, especially in intensive care settings and for patients with unstable hemodynamics [47,48]. Several non-invasive techniques, like bioimpedance, bioreactance, pulse wave transit time, ultrasonography, partial gas rebreathing, etc., have demonstrated the ability to measure CO continuously.

Thoracic Bioimpedance

Bioimpedance systems are based on the principle that the electrical resistance of blood changes with movement and fluctuations in volume. It relies on measured changes in signal amplitude of a transmitted electrical current via four electrodes placed on the neck and thorax [49]. Different equations are used to translate this into a stroke volume. The left ventricular ejection time is derived from the electrocardiogram.

A more recent tool to quantify CO is the endotracheal cardiac output monitor (ECOM). It uses an endotracheal tube with multiple electrodes attached to it which measures the changes in electrical bioimpedance caused by pulsatile blood flow in the aorta. The advantage of this device lies in the fact that instead of using multiple devices for haemodynamic monitoring, a single device helps in ventilation and CO monitoring. The disadvantage lies in the complexity of the placement of the device and the need for bronchoscopy for accurate positioning. The existing literature demonstrates conflicting and inconsistent results about the efficacy of this method in different clinical circumstances compared to the gold standard thermodilution techniques [50-53].

Thoracic Bioreactance

Bioreactance refers to the electrical resistive, capacitive, and inductive properties of blood and biological tissue that induce phase shifts between an applied electrical current and the resulting voltage signal [54]. This is not to be confused with bioimpedance, which describes the electrical characteristics of blood and tissue that control the voltage field amplitude that is produced when an electrical current is applied. Changes in thoracic blood volume during a heartbeat cause instantaneous changes in the phase shift between an applied current and the measured voltage signal, which can be quantitatively related to stroke volume and used to measure CO. Bioreactance has shown excellent performance for measuring CO and tracking CO changes during and after cardiac surgery and in the intensive care unit [55-57]. However, this technique has failed to obtain acceptable accuracy and precision for measuring CO during major abdominal surgeries and in patients with septic shock compared to those of thermodilution [58-60].

Pulse Wave Transit Time (PWTT)

In 2004, a new measurement method for determining continuous CO based on pulse contour analysis of the pulse-oximetry waveform and arterial pulse wave transit time (esCCO (estimated continuous cardiac output) system, Nihon Kohden, Tokyo, Japan) was introduced [61]. PWTT calculates the time between the rise of the photoplethysmography (PPG) waveform and the R-wave of the electrocardiogram by using the changes in finger blood volume determined by the PPG. PWTT is affected by changes in vascular volume, sympathetic nerve activity, and vascular elasticity [62]. The length of the PWTT is directly proportional to the blood pressure. In conditions where there is hyperdynamic circulation or peripheral arterial disease, pulse waves travel faster because blood flow reaches the peripheral site at a higher speed. The amplitude width and height indicate the changes in PWTT.

Standard clinical monitors check the NIBP at fixed time intervals, hence sudden critical blood pressure changes between these intervals may be missed. These changes are detected by PWTT and trigger an NIBP measurement. Therefore it helps the clinician identify adverse hemodynamic events in advance. Similar to other non-invasive technologies, this method has also demonstrated conflicting findings in comparison to invasive methods of CO measurement [63-65].

Partial Gas Rebreathing

This method uses partial carbon dioxide rebreathing (around 30 seconds) to determine continuous CO. Using the application of the Fick principle, CO is measured as the ratio of changes in CO_2 elimination ($\Delta V'CO_2$) to the partial pressure of end-tidal CO_2 ($\Delta PETCO_2$) following a short period of partial rebreathing. The main drawback is that all patients must be mechanically ventilated with fixed ventilator settings without spontaneous efforts. Patients with atelectasis, intrapulmonary shunts, circuit leaks, and variations in the ventilatory state are susceptible to biases in this approach.

Role of Ultrasound in Haemodynamic Monitoring

Ultrasound has become an indispensable tool in critical care settings. Transthoracic Echocardiography (TTE) and Trans-oesophageal Echocardiography (TEE) are the most reliable bedside methods to assess intravascular volume status, cardiac function and fluid responsiveness. Echocardiography as a point-of-care intervention has greatly increased the identification of real-time adverse cardiac events and the efficiency of goal-directed intraoperative haemodynamic monitoring and management [66-69]. ASA guidelines recommended the use of TEE in surgeries with a significant risk of hemodynamic, pulmonary, or neurological compromise [70]. Multiple studies have shown that there was no significant difference in the overall effect of the CO measurements by echocardiography or thermodilution techniques [71,72]. AI incorporated automatic calculations of real time ejection fraction, inferior vena cava diameter and velocity time integral have made it easier for the novice sonographer to incorporate these values during the management of a case.

Adequate Cardiac Output versus Adequate Perfusion

Cardiac output is a measure of the heart's overall pumping efficiency, while perfusion is a measure of blood flow and oxygen delivery to tissues. Although CO and mean arterial pressure are commonly measured to evaluate overall circulation, they don't always provide detailed insights into the adequacy of tissue perfusion or oxygen delivery. Recently, there has been a growing emphasis on understanding tissue perfusion.

Capillary refill time was one of the earliest indicators used to assess peripheral perfusion. Today, various global markers (such as mixed venous oxygen saturation, jugular vein oxygen saturation, central venous–arterial carbon dioxide difference, and lactate levels) and regional indicators (including cerebral oximetry, tissue oxygen electrodes, gastric mucosal CO_2 levels, and microdialysis catheters) are available to evaluate whether tissue perfusion is sufficient.

Perfusion Index

A Perfusion Index (PI) is a quantitative measure used in pulse oximetry to assess blood circulation at a specific site, such as a fingertip or earlobe, through photoplethysmography. It indicates the ratio of pulsatile blood flow to non-pulsatile blood within the tissue. A higher PI signifies good perfusion, whereas a lower PI may indicate poor perfusion. The PI has been evaluated for its effectiveness in assessing various hemodynamic factors, including perfusion adequacy, peripheral vascular resistance, fluid responsiveness, and predicting hypotension (with a PI > 3.5) after spinal anaesthesia, though results can vary. It is important to note that the PI value reflects regional arterial tone and may be influenced by local pathology without necessarily indicating systemic issues.

Cerebral and Tissue Oximetry

Like pulse oximetry, near-infrared spectroscopy (NIRS) uses spectrophotometry to estimate the percentage of oxyhaemoglobin. NIRS utilizes the near-infrared portion of the electromagnetic spectrum, ranging from 780 nm to 2500 nm, which is capable of penetrating various tissues like bone and muscle. Unlike pulse oximetry, NIRS does not incorporate plethysmography, and as a result, it does not distinguish between arterial and venous blood.

NIRS equipment provides regional tissue oxygen saturation (rSO_2) measurements at the sensor placement sites. Each organ has specific normal rSO_2 values, with normal cerebral rSO_2 being greater than 60%. Monitoring rSO_2 trends is more important than focusing solely on actual values. Any deviation from the baseline greater than 20% is considered abnormal and requires intervention. A significantly low rSO_2 indicates either increased oxygen consumption or decreased perfusion. NIRS's ability to detect regional hypoperfusion in cerebral, renal, and splanchnic tissues makes it a valuable tool for early identification of reduced organ perfusion and guiding therapies to restore it. The rSO_2 has proven to be beneficial in various high-risk clinical scenarios, including trauma, cardiac surgery, carotid endarterectomy, and critical

care. The main limitations are that specific organ therapeutic targets are not yet established and that, being a regional monitor, it may not reflect global perfusion status. Despite these limitations, NIRS technology is expected to play a crucial role in intraoperative monitoring in the coming years.

Machine Learning and Artificial Intelligence Based Devices

Artificial intelligence has started revolutionizing many fields of science and technology; the medical field is no exception. HemoSphere, developed by Edwards Lifesciences (Irvine, CA, USA), is an advanced monitor that integrates the Hypotension Prediction Index (HPI). It detects real-time changes in hemodynamic parameters and predicts those variations before they occur [73,74]. A prediction model was developed based on the characteristics of arterial waveforms. The HPI can predict a hypotensive episode at least five minutes prior to its onset. Higher numbers on the index, which ranges from 0 to 100, indicate a higher chance of hypotension. Multiple studies have shown the efficacy of this artificial intelligence tool in accurately predicting hypotensive episodes in advance and effectively minimizing hypotension episodes during surgeries [72-75].

Conclusion

The evolution of hemodynamic monitoring, from manual vital sign monitoring to the advent of advanced technologies like machine learning-based tools such as the Hypotension Prediction Index, has greatly enhanced our capabilities and insights. Modern instruments have replaced traditional manual approaches that provide precise, real-time data analysis. The field continues to seek more comprehensive and predictive monitoring systems. The history of hemodynamic monitoring demonstrates the commitment of healthcare professionals, scientists, and inventors to enhance patient care. Future advancements in understanding hemodynamics and developing superior monitoring technologies will definitely improve perioperative and intensive care outcomes. The field of hemodynamic monitoring has come a long way, but the best is probably yet to come.

References

1. Duncum B (1947) The development of inhalation anaesthesia, Part 9: The beginnings of modern anaesthesia. The Jubilee of Anaesthesia Geoffrey Cumberlege PP: 537-540.

2. Pierce EC (1988) Does monitoring have an effect on patient safety? Monitoring instruments have significantly reduced anesthetic mishaps. J Clinical Monit 4(2): 111-114.

3. Ali M, Ramachari A (1992) About the participants in the Hyderabad choloform commissions, PP: 28-31.

4. Clover JT (1876) On an apparatus for administering nitrous oxide gas and ether, singly or combined. British Med J 2(811): 74-75.

5. Kirk R (1896) On auscultation of the heart during chloroform narcosis. British Med J 2(1876): 1704-1706.

6. Teter CK (1909) Thirteen thousand administrations of nitrous oxide with oxygen as an anesthetic. J Am Med Ass LIII(6): 448-454.

7. Cushing H (1908) Technical methods of performing certain cranial operations.

8. Cohen S (1893) Exhibition of an oesophageal stethoscope, with remarks on intra-thoracic auscultation. Trans Coll Physicians Philadelphia 3(24): 218-221.

9. NS K (1905) On the subject of methods of measuring blood pressure. Bull Imp Military Med Scad St Petersburg 11: 365-367.

10. Von R (1901) Ueber Blutdruckmessung beim Menschen. Archiv fUr experimentelle Pathologie und Pharmakologie 46(1): 78-132.

11. Von R (1931) Neue Wege der Blutdruckmessung: 5 Abhandlungen über Blutdruck und Puls in der grossen Arterien des Menschen mit 68 Textabb 10 Grypotonogrammbildern u 4 Taf. Springer.

12. Lennox WG, Graves RC, Levine SA (1922) An electrocardiographic study of fifty patients during operation Archives of Internal Medicine 30(1): 57-72.

13. Maher C, Crittenden P, Shapiro P (1934) An electrocardiographic study of viscerocardiac reflexes during major operations. Am Heart J 9(5): 664-676.

14. Kurtz CM, Bennett JH, Shapiro HH (1936) Electrocardiographic studies during surgical anesthesia. J Am Medl Ass 106(6): 434-441.

15. Feil H, Rossman PL (1939) Electrocardiographic observations in cardiac surgery. Annals of Internal Med 13(3): 402-414.

16. Himmelstein A, Scheiner M (1952) The cardiotachoscope. Anesthesiology 13(1): 62-64.

17. Cannard TH, Dripps RD, Helwig J, Zinsser HF (1960) The electrocardiogram during anesthesia and surgery. Anesthesiology 21: 194-202.

18. Russell PH, Coakley CS (1969) Electrocardiographic

observation in the operating room. Anesthesia & Analgesia 48(5): 784.

19. Kaplan JA, King SB (1976) The precordial electrocardiographic lead (V5) in patients who have coronary-artery disease. Anesthesiology 45(5): 575-577.

20. Kaplan J (1979) Electrocardiographic monitoring. Cardiac Anesthesia PP: 149-151.

21. Cooper JB, Newbower RS, Kitz RJ (1984) An analysis of major errors and equipment failures in anesthesia management: Considerations for prevention and detection. Anesthesiology 60(1): 34-42.

22. Hales S (2024) Statical essays: Containing haemastaticks.

23. Peterson LH, Dripps RD, Risman GC (1949) A method for recording the arterial pressure pulse and blood pressure in man. Am Heart J 37(5): 771-782.

24. Peirce EC (1951) Percutaneous femoral artery catheterization in man with special reference to aortography. Surgery Gynecology & Obstetrics 93(1): 56-74.

25. Seldinger SI (1953) Catheter replacement of the needle in percutaneous arteriography; a new technique. Acta Radiologica 39(5): 368-376.

26. Klein O (1930) Zur bestimmung des zirkulatorischen minutenvolumens beim menschen nach dem fickschen prinzip. Munchen Med Wochenschr 77: 1311-1312.

27. Dexter L, Haynes FW, Burwell CS, Eppinger EC, Sagerson RP, et al. (1947) Studies of congenital heart disease. II. The pressure and oxygen content of blood in the right auricle, right ventricle, and pulmonary artery in control patients, with observations on the oxygen saturation and source of pulmonary "capillary" blood. J Clinical Inves 26(3): 554-560.

28. Lagerlof H, Werko L (1949) Studies on the circulation of blood in man vi. The pulmonary capillary venous pressure pulse in man. Scandinavian J Clin Laboratory Invest.

29. Swan HJC, Ganz W, Forrester J, Marcus H, Diamond G, et al. (1970) Catheterization of the heart in man with use of a flow-directed balloon-tipped catheter. Eng J Med 283(9): 447-451.

30. Shah MR, Hasselblad V, Stevenson LW, Binanay C, Connor CM, et al. (2005) Impact of the pulmonary artery catheter in critically ill patientsmeta-analysis of randomized clinical trials. JAMA 294(13): 1664-1670.

31. Michard F, Teboul JL (2002) Predicting fluid responsiveness in ICU patients: A critical analysis of the evidence. Chest 121(6): 2000-2008.

32. Vincent JL, Sakr Y, Sprung CL, Ranieri VM, Reinhart K, et al. (2006) Sepsis in European intensive care units: Results of the SOAP study. Critical Care Med 34(2): 344.

33. Marik PE, Monnet X, Teboul JL (2011) Hemodynamic parameters to guide fluid therapy. Annals of Intensive Care 1(1): 1.

34. Perel A (2020) Using dynamic variables to guide perioperative fluid management. Anesthesiology 133(4): 929-935.

35. Monnet X, Shi R, Teboul JL (2022) Prediction of fluid responsiveness. What's new? Annals of Intensive Care 12(1): 46.

36. Gopal J, Srivastava S, Singh N, Haldar R, Verma R, et al. (2023) Pulse pressure variance (PPV)-guided fluid management in adult patients undergoing supratentorial tumor surgeries: A randomized controlled trial. Asian J Neurosurgery 18: 508-515.

37. Funk DJ, Moretti EW, Gan TJ (2009) Minimally invasive cardiac output monitoring in the perioperative setting. Anesthesia & Analgesia 108(3): 887.

38. Hofer CK, Ganter MT, Zollinger A (2007) What technique should I use to measure cardiac output? Current Opinion in Critical Care 13(3): 308.

39. Rhodes A, Sunderland R (2005) Arterial pulse power analysis: The LiDCO$\mathcal{M}$ plus System. In Pinsky MR, et al. (Eds.), Functional Hemodynamic Monitoring, Springer, pp: 183-192.

40. Waal EEC, Wappler F, Buhre WF (2009) Cardiac output monitoring. Current Opinion in Anaesthesiology 22(1): 71-77.

41. Colquhoun DA, Roche AM (2014) Oesophageal Doppler cardiac output monitoring: A longstanding tool with evolving indications and applications. Best Practice & Research Clinical Anaesthesiology 28(4): 353-362.

42. Chamberlain BM, Willshire RJ (2010) Oesophageal Doppler Monitor (ODM) guided individualised goal directed fluid management (iGDFM) in surgery-a technical review. Surgery 19: 21.

43. Dark PM, Singer M (2004) The validity of trans-esophageal Doppler ultrasonography as a measure of cardiac output in critically ill adults Intensive. Care Med 30(11): 2060-2066.

44. Schober P, Loer SA, Schwarte LA (2009) Perioperative hemodynamic monitoring with transesophageal Doppler technology. Anesthesia and Analgesia 109(2): 340-353.

45. Missant C Rex S, Wouters PF (2008) Accuracy of cardiac output measurements with pulse contour analysis (PulseCO) and Doppler echocardiography during off-pump coronary artery bypass grafting. European J Anaesthesiology 25(3): 243-248.

46. Sharma J, Bhise M, Singh A, Mehta Y, Trehan N (2005) Hemodynamic measurements after cardiac surgery: Transesophageal Doppler versus pulmonary artery catheter. J Cardiothoracic and Vascular Anesthesia 19(6): 746-750.

47. Joosten A, Desebbe O, Suehiro K, Murphy L, Essiet M, et al. (2017) Accuracy and precision of non-invasive cardiac output monitoring devices in perioperative medicine: A systematic review and meta-analysis. British J Anaesthesia 118(3): 298-310.

48. Squara P, Imhoff M, Cecconi M (2015) Metrology in Medicine: From Measurements to Decision, with Specific. Reference to Anesthesia and Intensive Care Anesthesia & Analgesia 120(1): 66-75.

49. Water JM, Miller TW, Vogel RL, Mount BE, Dalton ML (2003) Impedance cardiography: The next vital sign technology? Chest 123(6): 2028-2033.

50. Krzesinski P, Jankowska EA, Siebert J, Galas A, Piotrowicz K, et al. (2022) Effects of an outpatient intervention comprising nurse-led non-invasive assessments, telemedicine support and remote cardiologists' decisions in patients with heart failure (AMULET study): A randomised controlled trial. European J Heart Failure 24(3): 565-577.

51. Lu Y, Wang L, Wang H, Gu J, Ma ZJ, et al. (2021) Effectiveness of an impedance cardiography guided treatment strategy to improve blood pressure control in a real-world setting: Results from a pragmatic. clinical trial Open Heart 8(2): e001719.

52. Sanders M, Servaas S, Slagt, C (2020) Accuracy and precision of non-invasive cardiac output monitoring by electrical cardiometry: A systematic review and meta-analysis. J Clinical Monitoring and Computing 34(3): 433-460.

53. Panagiotou M, Vogiatzis I, Jayasekera G, Louvaris Z, Mackenzie A, et al. (2018) Validation of impedance cardiography in pulmonary arterial hypertension. Clinical Physiology and Functional Imaging 38(2): 254-260.

54. Keren H, Burkhoff D, Squara P (2007) Evaluation of a noninvasive continuous cardiac output monitoring system based on thoracic bioreactance. Am J Physiology Heart and Circulatory Physiol 293(1): H583-589.

55. Doherty A, Khuffash A, Monteith C, McSweeney L, Breatnach C, et al. (2017) Comparison of bioreactance and echocardiographic non-invasive cardiac output monitoring and myocardial function assessment in primagravida women. British Journal of Anaesthesia 118(4): 527-532.

56. Waldron NH, Miller TE, Thacker JK, Manchester AK, White WD, et al. (2014) A prospective comparison of a noninvasive cardiac output monitor versus esophageal Doppler monitor for goal-directed fluid therapy in colorectal surgery patients. Anesthesia and Analgesia 118(5): 966-975.

57. Cheung H, Dong Q, Dong R, Yu B (2015) Correlation of cardiac output measured by non-invasive continuous cardiac output monitoring (NICOM) and thermodilution in patients undergoing off-pump coronary artery bypass surgery. Journal of Anesthesia 29(3): 416-420.

58. Hagege E, Teboul JL, Artigas A, Talbot A, Sabatier C, et al. (2013) Bioreactance is not reliable for estimating cardiac output and the effects of passive leg raising in critically ill patients. British J Anaesthesia 111(6): 961-966.

59. Conway DH, Hussain OA, Gall I (2013) A comparison of noninvasive bioreactance with oesophageal Doppler estimation of stroke volume during open abdominal surgery: An observational study European. J Anaesthesiology 30(8): 501-508.

60. Han S, Lee JH, Kim G, Ko JS, Choi SJ, et al. (2015) Bioreactance Is Not Interchangeable with Thermodilution for Measuring Cardiac Output during Adult Liver Transplantation. PloS One 10(5): e0127981.

61. Ishihara H, Okawa H, Tanabe K, Tsubo T, Sugo Y, et al. (2004) A new non-invasive continuous cardiac output trend solely utilizing routine cardiovascular monitors. J Clinical Monitoring and Computing 18(5-6): 313-320.

62. Ochiai R, Takeda J, Hosaka H, Sugo Y, Tanaka R, et al. (1999) The relationship between modified pulse wave transit time and cardiovascular changes in isoflurane anesthetized dogs. J Clinical Monitoring and Computing 15(7-8): 493-501.

63. Fukui K, Wirkus JM, Hartmann EK, Schmidtmann I, Pestel GJ, et al. (2023) Non-invasive assessment of Pulse Wave Transit Time (PWTT) is a poor predictor for intraoperative fluid responsiveness: A prospective observational trial

(best-PWTT study). BMC Anesthesiology 23(1): 60.

64. Yamada T, Tsutsui M, Sugo Y, Sato T, Akazawa T, et al. (2012) Multicenter study verifying a method of noninvasive continuous cardiac output measurement using pulse wave transit time: A comparison with intermittent bolus thermodilution cardiac output. Anesthesia and Analgesia 115(1): 82-87.

65. Joshi M, Rathod R, Bhosale SJ, Kulkarni AP (2022) Accuracy of Estimated Continuous Cardiac Output Monitoring (esCCO) Using Pulse Wave Transit Time (PWTT) Compared to Arterial Pressure-based CO (APCO) measurement during major surgeries. Indian J Critical Care Medicine 26(4): 496-500.

66. Barber RL, Fletcher SN (2014) A review of echocardiography in anaesthetic and peri-operative practice Part 1: Impact and utility. Anaesthesia 69(7): 764-776.

67. Petersen JW, Liu J, Chi YY, Lingis M, Williams RS, et al. (2017) Comparison of multiple non-invasive methods of measuring cardiac output during pregnancy reveals marked heterogeneity in the magnitude of cardiac output change between women. Physiological Reports 5(8).

68. Bergamaschi V, Vignazia GL, Messina A, Colombo D, Cammarota G, et al. (2018) Transthoracic echocardiographic assessment of cardiac output in mechanically ventilated critically ill patients by intensive care unit physicians. Brazilian Journal of Anesthesiology 69(1): 20-26.

69. Souza RS, Melo WB, Freire CM, Vilas B (2023) Comparative study between suprasternal and apical windows: A user-friendly cardiac output measurement for the anesthesiologist. Brazilian J Anesthesiology 73(4): 373-379.

70. (2010) American Society of Anesthesiologists and Society of Cardiovascular Anesthesiologists Task Force on Transesophageal Echocardiography. Practice guidelines for perioperative transesophageal echocardiography An updated report by the American Society of Anesthesiologists and the Society of Cardiovascular Anesthesiologists Task Force on Transesophageal Echocardiography Anesthesiology 112(5): 1084-1096.

71. Keller M, Magunia H, Rosenberger P, Koeppen M (2023) Echocardiography as a tool to assess cardiac function in critical care-A Review. Diagnostics 13(5): 839.

72. Zhang Y, Wang Y, Shi J, Hua Z, Xu J (2019) Cardiac output measurements via echocardiography versus thermodilution: A systematic review and meta-analysis. PloS One 14(10).

73. Davies SJ, Vistisen ST, Jian Z, Hatib F, Scheeren TWL (2020) Ability of an arterial waveform analysis-derived hypotension prediction index to predict future hypotensive events in surgical patients Anesthesia and Analgesia 130(2): 352-359.

74. Hatib F, Jian Z, Buddi S, Lee C, Settels J, et al. (2018) Machine-learning algorithm to predict hypotension based on high-fidelity arterial pressure waveform analysis Anesthesiology 129(4): 663-674.

75. Tsoumpa M, Kyttari A, Matiatou S, Tzoufi M, Griva P, et al. (2021) The use of the hypotension prediction index integrated in an algorithm of goal directed hemodynamic treatment during moderate and high-risk Surgery. J Clinical Med 10(24): 5884.