ISSN: 0975-3583,0976-2833 VOL15, ISSUE 12, 2024

Agreement between the Multi-Beat Analysis algorithm for cardiac output estimation and trans-thoracic 2D echocardiography in the ICU.

Dr. SanjithSaseedharan, DR.AALIA THINGNA, Dr Ganesh Shingade, Dr Komal Pawar, Dr Vaijayanti Kadam

Head of Department of Critical Care Medicine at S L Raheja Hospital (A Fortis Associate)
Orcid ID-0000-0003-4299-4317
Corresponding Author- DR.AALIA THINGNA
ICU Registrar at S L Raheja Hospital (A Fortis Associate)
Address: S L Raheja Hospital Fortis, Raheja Hospital Road, Mahim, Mumbai - 400016, Opposite Police Colony
Orchid ID-0000-0003-4109-1220

Associate Consultant at S L Raheja Hospital (A Fortis Associate)
Address: S L Raheja Hospital Fortis, Raheja Hospital Road, Mahim, Mumbai - 400016, Opposite Police Colony
Consultant Cardiologist at S L Raheja Hospital (A Fortis Associate)
Consultant Intensivist at S L Raheja Hospital (A Fortis Associate)

Abstract

Objective: Cardiac output (CO) and stroke volume (SV) monitoring are cornerstones of hemodynamic management in patients at risk of shock. The multi-beat analysis (MBA) method provides continuous estimates of CO and SV by analysis of a patient's arterial blood pressure waveform. In this study we assessed the agreement of CO and SV between 2D echocardiography (CO-ECHO and SV-ECHO) and the multi-beat analysis (MBA) method via the Argos monitor (CO-MON and SV-MON). 2 D echo is used in this study for comparison, as there are several complications such as pneumothorax, infection, bleeding etc associated with the gold standard, i.e. pulmonary artery catheterization, as it is a highly invasive procedure. There are several existing studies proving that data obtained from 2 D echo is as accurate as that obtained from PAC, and as this is a routine investigation done in the ICU setting, 2 D echo was chosen to assess the accuracy of MBA.

Design:Observational, method comparison study

Place and Duration of study:Intensive care unit a tertiary care hospital from 3/08/2022 to 3/11/2022.

Methodology:Data from fifty patients with a wide range of diagnoses in the ICU was analyzed in this. One set of paired, simultaneous measurements was recorded for each patient.

Results:The mean difference between CO-ECHO and CO-MON was -0.05 ± 0.58 L/min with limits of agreement from -1.18 to +1.08 L/min and a percentage error of 21.5%. The mean difference between SV-ECHO and SV-MON was -0.9 ± 6.6 mL with limits of agreement from -13.9 to +12.0 mL and a percentage error of 22.8%.

ISSN: 0975-3583,0976-2833 VOL15, ISSUE 12, 2024

Conclusion: Accuracy of the MBA method was clinically acceptable as compared to 2D echocardiography.

Keywords:cardiac output, hemodynamic monitoring, stroke volume

1. Introduction

Current guidelines for assessing and treating circulatory shock call for hemodynamic monitoring to be started as early as possible.[1,2] When further hemodynamic monitoring is needed, it is suggested that echocardiography be used to determine shock etiology.[1] While valuable as an assessment tool, echocardiography is resource-intensive and requires specialized training, which can delay immediate deployment for a patient in shock. Further, it provides only intermittent snapshots of the patient's status. Pulse-contour analysis methods estimate stroke volume (SV) and cardiac output (CO) continuously from a patient's arterial blood pressure waveform and can supplement echocardiography if demonstrated to be accurate.[3] The purpose of this study was to assess agreement between two methods of SV and CO estimation – a) transthoracic 2D echocardiograph, and b) a new pulse contour analysis method that uses a multi-beat analysis algorithm.

The multi-beat analysis (MBA) method is available commercially on the Argos hemodynamic monitor (Retia Medical Systems Inc., White Plains, NY, USA). The MBA method analyzes multiple beats in a 20-second segment of the arterial BP waveform signal and provides updated estimates of SV, CO, systemic vascular resistance (SVR) every 5 seconds. The MBA method attempts to account for the confounding effects of BP wave reflections due to sites of resistance (arterial bifurcations and arterioles).[4] First, the MBA algorithm uses multiple beats to model the complete vascular response to a cardiac ejection event. Next, the algorithm analyses the smooth exponential decay of the vascular response after the wave reflections have subsided to estimate the time constant of the vascular system.[4] This time constant τ is a product of two vascular characteristics: the arterial compliance (AC) and the systemic vascular resistance (SVR). AC is estimated from a nomogram based on the patient's age, sex, height, weight and arterial BP, therefore allowing a calculation of the SVR from the equation $SVR = \tau/AC$. CO and SV follow from the equations $CO = MAP/SVR$; and $SV = CO/HR$. Previous validation studies in cardiac surgical, heart failure, abdominal and neuro surgery patients show promising results, but the MBA algorithm accuracy remains to be validated in non-cardiac ICU patients. [5-9]

2. Methods

This study was conducted at a tertiary care centerafter review and approval by the institutional ethics committee. The ethics committee also determined that the study design met the criteria for a waiver of patient informed consent. Patients were enrolled in this prospective study from August 2022 to January 2023 in the ICU. This was an observational, descriptive study with no testable hypotheses. A previous pilot study was conducted in the same institute, with a small sample size of 15 patients which showed promising data, after which this study was conducted. The sample size has been calculated as 50 based on the data obtained from the pilot study.

ISSN: 0975-3583,0976-2833 VOL15, ISSUE 12, 2024

Study inclusion criteria were 1) Adult patients (Age ≥ 18 years) admitted to the ICU; and 2) Arterial line catheter inserted for invasive blood pressure waveform monitoring per standard of care. These inclusion criteria were necessary to identify patients eligible to be monitored by the Argos device, per the indications for the device.

Study exclusion criteria were 1) Mechanical circulatory support - LVADs (Left Ventricular Assist Device), IABP (Intra-Aortic Balloon pump), or arterial ECMO (Extra-Corporeal Membrane Oxygenation); 2) Over or under damped arterial line; 3) Low ejection fraction (EF < 40%) ; 4) Post cardiac surgery; 5) Patients with triple high dose inotropic support; (Noradrenaline > 1 mcg/kg/minute, Adrenaline > 0.5 mcg/kg/minute, Vasopressin > 0.04 units/minute); 6) Moderate to severe aortic or mitral regurgitation; 7) Cardiac arrhythmias, such as atrial fibrillation or supraventricular tachycardia; and 8) Chest trauma or chest surgery.

The intent of the inclusion/exclusion criteria is to assess the accuracy of the MBA method in a non-cardiac but otherwise diverse population as presented in a typical mixed ICU, which do not present with acute hemodynamic instability. Patients with Low EF were not included to test the MBA method in a relatively cardiac-stable population. Patients of chest trauma and surgery were excluded due to difficult echo window in such patients. Although it is desirable to know the agreement over a large range of CO and SV values, including low EF patients. Due to the limited scope of the study, we will take a step-by-step approach, with the first step being a comparison in a non-cardiac population. The next step would be a study to investigate the agreement in cardiac unstable populations.

The first criterion, mechanical circulatory support, is a contraindication for the Argos monitor. The second criterion, over or under-damped arterial-line, was objectively quantified with a fast flush test. This criterion was applied to exclude the analysis of non-physiological BP waveforms by the Argos monitor. Less than two waveform oscillations after the fast flush indicated that the line was overdamped, while more than three oscillations indicated an underdamped arterial line. The remaining exclusion criteria were applied to obtain a study population without any cardiac issues, in order to test the MBA method in a relatively cardiac-stable population. Moreover, presence of arrhythmias may affect the accuracy of data obtained by both methods, hence these patients were excluded.

All 2D echocardiography measurements were performed by a qualified cardiologist (postgraduate degree in cardiology)trained in performing 2D echocardiograms,using a Samsung HS40/XH 40 echocardiography machine. To eliminate bias, the cardiologist was blinded to SV and CO measurements from the Argos monitor. The monitor was covered with a sterile green cloth while the cardiologist was performing the echocardiography. Left ventricular end-diastolic volume (EDV) and end-systolic volume (ESV) were calculated using the modified Simpson's biplane method and averaged over 3 heartbeats, as recommended by ASE guidelines.[10] Stroke volume (SV) was then calculated as EDV – ESV. Cardiac Output (CO) was obtained by multiplying the stroke volume with heart rate from the patient monitor (CO = SV x HR). This process was repeated 3 times. SV and CO were average over these 3 measurements to reduce operator variability.

ISSN: 0975-3583,0976-2833 VOL15, ISSUE 12, 2024

Blood pressure waveform was obtained using a radial arterial line and transduced and monitored on the patient bedside monitor (Phillips IntelliVue) per the standard of care at our institution. A fast flush test was done on the arterial line prior to study measurements to ensure that the waveform was not over or under-damped. Patients with an over or under-damped a-lines were excluded from further analysis.

The Argos monitor was connected via a re-usable cable to the patient monitor in order to receive the blood pressure waveform. Simultaneous to the determination of SV and CO via 2D echo (SV-ECHO and CO-ECHO), SV and CO measurements from the Argos monitor were noted down (SV-MON and CO-MON). Each set of paired measurements was performed once on each enrolled patient within 48 hours of admission.

The collected data were analyzed with IBM SPSS Statistics for Windows, Version 23.0.(IBM Corp, Armonk, NY, USA). Patient demographics and vital signs were summarized using frequency counts for categorical variables and the mean, standard deviation (SD), minimum and maximum values for continuous variables. Patient diagnoses were also noted and summarized.

Bland-Altman analysis (means difference ± SD, limits of agreement and percentage error) was used to assess the agreement between SV and CO estimated from each of the two methods.[11] In addition, the correlation coefficient and Cronbach's Alpha were calculated to assess the strength of the linear relationship and the reliability between the two methods. Accounting for effects due to repeated measurements within subjects (within-subject variability) was not necessary as only a single paired measurement was taken from each patient. Results therefore only indicate the inter-subject variability.

We used the Critchley and Critchley criterion to determine if the agreement between the two methods of CO estimation was clinically acceptable.[12] This criterion was originally proposed by Critchley and Critchley to evaluate agreement between the reference thermodilution method and another test method for CO estimation. The agreement is clinically acceptable if the percentage error between them is less than 30%. [13] While not strictly applicable here as the reference method is 2D echocardiography, it nonetheless serves as a useful benchmark in the absence of other accepted criteria.

The Agreement: Tolerability Index (ATI) was proposed by Crossingham et al. 2016 as a metric that takes into account the clinical tolerance limit beyond which an intervention will be made, when comparing the agreement between two CO measurement techniques. ATI is defined as ATI = (Upper limit of agreement – Lower limit of agreement)/maximum clinical tolerability interval.[14] As recommended by Crossingham et al., we used a maximum clinical agreement tolerability interval of 1.6 L/min/m2 for the cardiac index (CI). Following the same methodology as Crossingham et al., we multiplied the CI tolerability interval by a factor of 1.73 m2 (population mean of body surface area) to obtain a CO tolerability interval of 2.77 L/min. Per Crossingham et al., an index of more than 2.0 expresses an unacceptable agreement, an index between 1.0 to 2.0 indicates marginal agreement, and an index less than 1.0 indicates acceptable agreement.

3. Results

ISSN: 0975-3583,0976-2833 VOL15, ISSUE 12, 2024

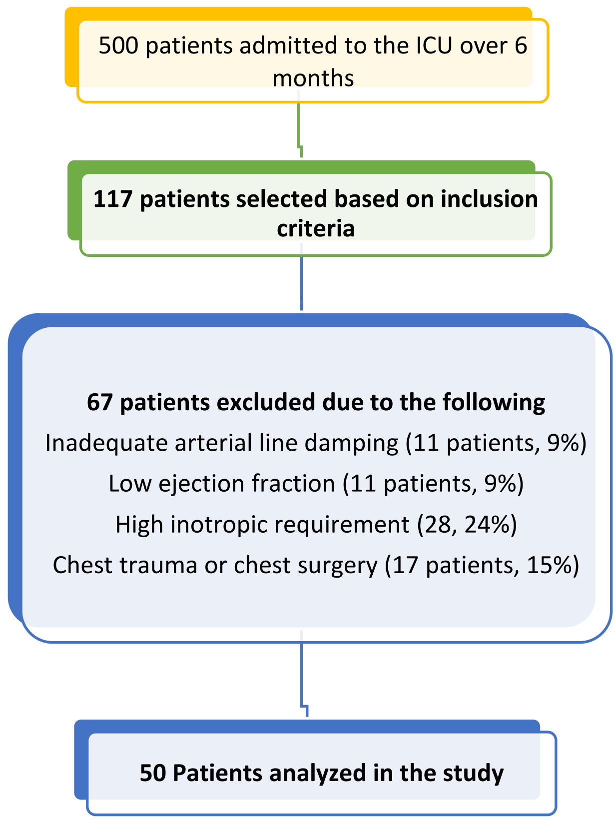

Figure 1
This flow chart represents the number of patients included in the study, and the percentage excluded based on the inclusion and exclusion criteria.

Table 1. Patient characteristics

	Mean	Standard Deviation (SD)	Minimum	Maximum
Number of patients	50			
Age (years)	61.2	13.9	27	87
Sex (F/M)	26 F / 24 M			
Weight (kg)	65.0	10.2	45	98
Heart rate (bpm)	94.2	19.1	60	132
Systolic BP (mmHg)	128.5	19.3	98	171
Diastolic BP (mmHg)	70.8	11.6	46	94

Of the 500 patients admitted to the ICU during the study period, 117 patients met the inclusion criteria. Of these, sixty-seven patients were excluded due to the exclusion criteria (Fig. 1). After exclusions, data from fifty patients was analyzed. One paired measurement (Echo and Argos) was obtained from each of these fifty patients. Overall patient demographics and vital signs are shown in Table 1. CO-2D ECHO across all patients was 5.2 ± 1.4 L/min (Mean ± SD), while CO-MON was 5.3 ± 1.6 L/min. SV-2D ECHO across all patients was 56.3 ± 15.5 ml, while SV-MON was 57.3 ± 16.2 ml.

Table 2. Primary diagnosis for ICU admission

Diagnosis	Number of patients	Percent
Acute exacerbation of COPD (Chronic obstructive pulmonary disease)	2	4.0
Adenocarcinoma of colon	1	2.0
Acute kidney injury	1	2.0
Aspiration pneumonia	2	4.0
Carcinoma - Gall bladder	1	2.0
Carcinoma - lung	1	2.0
Carcinoma - rectum	1	2.0
Cancer of buccal mucosa	2	4.0
Dengue shock	2	4.0
Diabetic foot	3	6.0
Encephalitis	1	2.0
Intestinal obstruction	2	4.0
Left MCA (Middle Cerebral Artery) infarct	1	2.0
Leptospirosis	1	2.0
Lower respiratory tract infection	4	8.0
Left ventricular failure	1	2.0
Myocardial Infarction	1	2.0
Multiple myeloma	1	2.0

ISSN: 0975-3583,0976-2833 VOL15, ISSUE 12, 2024

Diagnosis	Number of patients	Percent
Pancreatitis	1	2.0
Peripheral vascular disease	1	2.0
Pneumonia	6	12.0
Renal tubular acidosis	1	2.0
Sepsis	4	8.0
Septic shock	4	8.0
Stroke	1	2.0
Urosepsis	2	4.0
Urinary tract infection	1	2.0
Viral pneumonia	1	2.0
Total	**50**	**100.0**

Table 2 shows the diversity of clinical conditions and diagnoses in this patient population in the ICU. Sepsis in the study was diagnosed using the latest definition of sepsis and qSOFA scoring.[15] From the data collected, 30 patients were in sepsis with different infective focuses and 7 patients had cancer. Although the purpose of the exclusion criteria was to exclude cardiac patients, two patients with cardiac conditions were included in the final analysis as they did not meet the exclusion criteria. For the patient with left ventricular failure, EF was 40% and for the patient with a myocardial infarction, EF was 50%. Six patients (12%) were on noradrenaline (norepinephrine) support, while two patients (4%) were on nitroglycerine.

ISSN: 0975-3583,0976-2833 VOL15, ISSUE 12, 2024

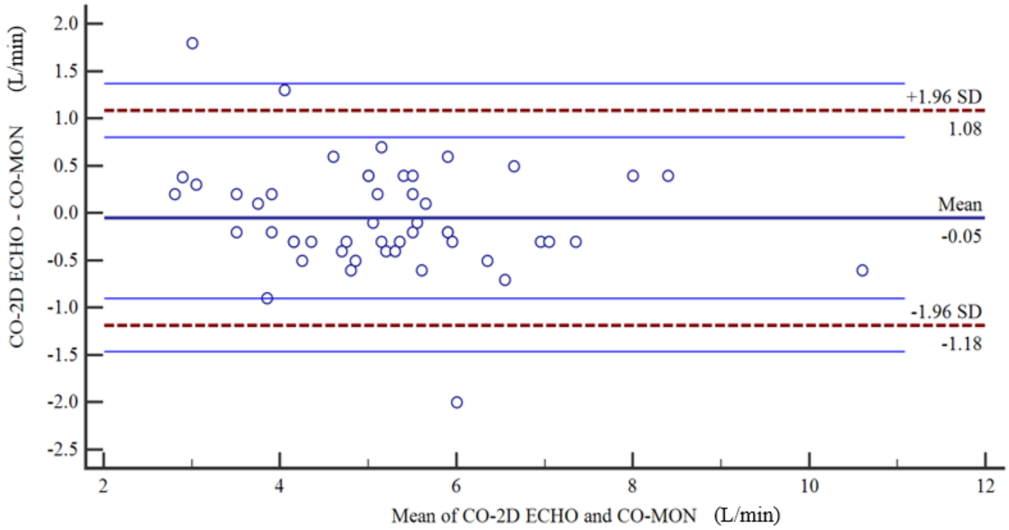

Fig. 2. Bland-Altman plot showing agreement between CO-ECHO and CO-MON. The bold blue line indicates the bias, and dashed red lines indicate the limits of agreement. 95% confidence intervals around the limits of agreement are shown in thin blue lines.

Fig. 2 shows the agreement of cardiac output estimates between 2D Echocardiography (CO-2D ECHO) and the MBA method via the Argos monitor (CO-MON) on a Bland-Altman plot. The mean difference between CO-2D ECHO and CO-MON was -0.05 ± 0.58 L/min, with 95% limits of agreement of -1.18 to +1.08 L/min. The percentage error was 21.5%. The correlation coefficient between the two methods was 0.91 [0.85 – 0.95] and Cronbach's Alpha value was 0.95. Of the 50 total CO data points, there were three pairs that had the same numerical values. These 3 pairs of points overlap when graphed on the Bland Altman plot, making it appear that there are 47 data points.The ATI (agreement:Tolerability Index, Crossingham et. al. 2016) between echocardiography and the Argos monitor was 0.82 [95% CI 0.71 - 0.93] , indicating acceptable agreement (ATI < 1.0).

ISSN: 0975-3583,0976-2833 VOL15, ISSUE 12, 2024

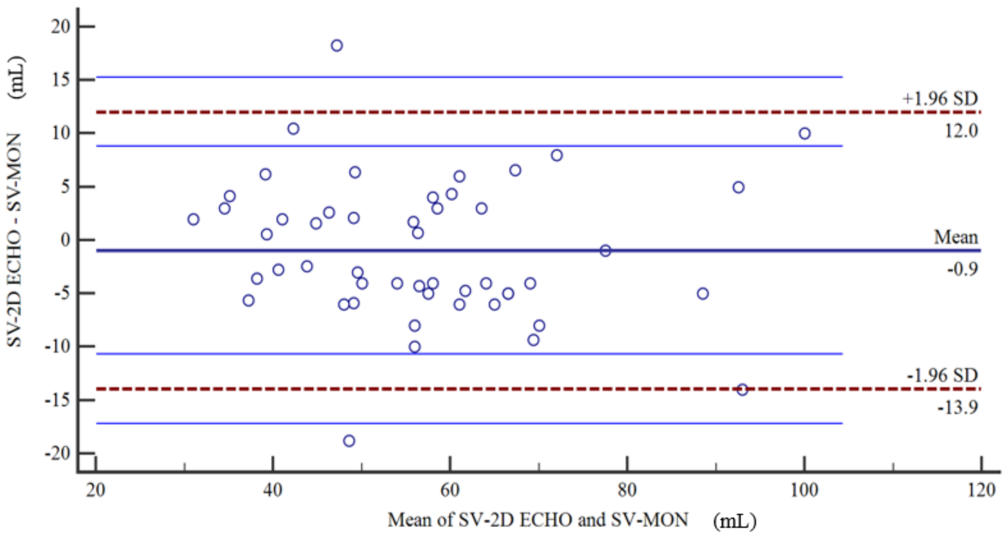

Fig. 3. Bland-Altman plot showing agreement between SV-ECHO and SV-MON. The bold blue line indicates the bias, and dashed red lines indicate the limits of agreement. 95% confidence intervals around the limits of agreement are shown in thin blue lines.

Fig. 3 shows the agreement of stroke volume estimates between 2D Echocardiography (SV-2D ECHO) and the MBA method via the Argos monitor (SV-MON) on a Bland-Altman plot. The mean difference between SV-2D ECHO and SV-MON was -0.9 ± 6.6 mL, with 95% limits of agreement of -13.9 to +12.0 mL. The percentage error was 22.8%. The correlation coefficient between the two methods was 0.93 [0.87 – 0.96] and Cronbach's Alpha value was 0.96. Of the 50 total SV data points, there was one pair that had the same numerical values. This pair of points overlap when graphed on the Bland Altman plot, making it appear that there are 49 data points.

4. Discussion

In this study we compared agreement between two methods of cardiac output and stroke volume estimation. The reference method was volumetric estimation via transthoracic 2D echocardiography and the test method was the MBA algorithm via the Argos monitor. Over a diverse patient population and hemodynamic conditions, the results from this observational study point to possible agreement between the MBA method and 2D echocardiography. The Critchley and Critchley criterion applied to the results to interpret clinical agreement is a post-hoc criterion and therefore not statistically conclusive.[12]

The clinical reference standard for cardiac output measurements is considered to be the thermodilution method via a pulmonary artery catheter (PAC). In our study we used 2D echocardiography as the reference method. Due to the risk of infection and other life-threatening complication, the PAC is used for monitoring in only a fraction of high-risk cardiac or liver transplant cases.[16] There are conflicting data on the agreement between CO/SV measurements from echocardiography vs thermodilution, with one meta-analyses concluding that differences between the two methods are not significant[17], while another concluding that the two methods are not interchangeable[18]. Nonetheless, for patients in whom the PAC is not indicated, including non-cardiac patients, shock assessment via echocardiography remains the only available option and was therefore used as the reference method in this study[19] We used

Simpson's method to measure LV chamber size (ESV and EDV) as recommended by the American Society of Echocardiography.[10]

Montenij et al 2016 recommend that the primary method of assessing agreement between two Cardiac Output methods should be the Bland-Altman analysis, with correlation analysis as a secondary analysis. We therefore provide correlation coefficient and Cronbach's alpha analyses as additional information. In our study we found that correlation coefficient was 0.91/0.93 for CO/SV and Cronbach's alpha was 0.95/0.96 which are high, but we do not discuss it further since there are no clinically accepted thresholds for 'acceptable agreement'.[20]

Previous method comparison studies investigating the accuracy of the MBA method against the thermodilution method have shown promising results in heart failure and cardiac surgery patients in the OR and ICU.[5-7, 9] In patients undergoing abdominal or neuro surgery, the MBA method was able to track changes in CO accurately after vasopressor or fluid interventions, when using the esophageal Doppler as a reference.[8] To our knowledge, this is the first study comparing CO and SV values from the MBA algorithm to 2D echocardiography in non-cardiac patients in the ICU with a wide range of diagnoses.

Although the percentage errors seem high but even the best cardiac output measurement devices available in the clinic – the Swan-Ganz catheter and echocardiography - have an inherent error of 20-30% [21]. This is why the Critchley and Critchley criteria has been set at 30% by the experts in this field. Within arterial pulse wave analysis-based algorithms, Peyton and Chong's meta-analysis found that most such devices in fact have a 40-45% error.[22] In this context, the 21-23% error we found was acceptable and better than other similar devices available commercially. This may be due to the MBA algorithm being the latest generation of this technology. In our data, the average BP was indeed 128.5/70.8, but the hemodynamics spanned a wide range: HR from 60 to 132; Systolic BP from 98 to 171, Diastolic BP from 46 to 94; CO from 3-10; SV from 30-100. Therefore our data cannot be extrapolated to suggest that the device remains accurate as shock progresses, another study should be done to investigate that question.

A limitation of our study is that we were unable to assess the trending ability of the monitor due to only a single set of measurements for each patient. Further studies are needed to assess the ability of the MBA algorithm to SV and CO changes in non-cardiac ICU patients. Another limitation is that the echocardiography measurements were performed by a single operator. This could have introduced operator bias within the echo measurements. There is evidence that 2D echocardiography may underestimate LV volumes.[23] Three-dimensional echocardiography may offer improved accuracy but is unavailable at our institution. We excluded patients requiring higher doses of ionotropic support, and those with poor ejection fraction, as the aim of this study was to compare the two methods patients without any cardiac pathology. However further studies targeting this population are required to further assess the reliability of this method. The intent of the study was to assess the accuracy of the MBA method in a non-cardiac but otherwise diverse population as presented in a typical mixed ICU. Representation of a select non cardiac patient population due to exclusion of patients with mechanical circulatory failure ,high doses of inotropes, ejection fraction less than 40%etc, was done to assess MBA in critical patients with relatively normal cardiac functions. This is the first step in determining the

ISSN: 0975-3583,0976-2833 VOL15, ISSUE 12, 2024

accuracy of the method, and future studies should explore the accuracy of the monitor in more detail, in patients with specific shock conditions and on specific therapeutic agents. Further the temporal profile of the illness and stage at which the measurements are taken should be recorded and studied. Finally, this was a single-center study and results may not generalize across other institutions, particularly due to different patient populations.

5. Conclusion

The results from this observational study point to possible agreement between the MBA method and 2D echocardiography. These data serve as pilot data for a larger, appropriately powered statistical study that can conclusively answer this question. We also clarify that the Critchley and Critchley criterion applied to the results to interpret clinical agreement is a post-hoc criterion and therefore not statistically conclusive.The ATI (Agreement:Tolerability Index, Crossingham et. al. 2016) between echocardiography and the Argos monitor was 0.82 [95% CI 0.71 - 0.93] , indicating acceptable agreement (ATI < 1.0).Echocardiography provides detailed views to assess structural abnormality andcardiacfunction, but is intermittent and requires trained personnel. The MBA method is a continuous measurement and is suitable to supplement echocardiography in clinical practice, in patients without mechanical circulatory support , low ejection fraction (EF < 40%), post cardiac surgery, patients with triple high dose inotropic support, and patients with cardiac conditions. Further studies would be required to assess the accuracy of the device in this patient population. Furthermore, the device wasn't tested on its ability of continuous haemodynamic monitoring in this study, as the aim was to compare the data obtained via MBA versus 2 D echo, hence further studies should aim to assess the accuracy of MBA for continuous monitoring.

List of abbreviations

CO = cardiac output
SV = stroke volume
MBA = multi beat analysis
2D ECHO = 2 dimensional echocardiography
ICU = intensive care unit
AC = arterial compliance
SVR = systemic vascular resistance
PAC = pulmonary artery catheter
SV-MON = stroke volume- MBA method via the Argos monitor
LV = left ventricle
TD- thermodilution
LVAD-left ventricular assist device
ECMO- Extracorporeal membrane oxygenation
COPD- Chronic obstructive pulmonary disease
BP-Blood Pressure
CA- Carcinoma

MCA-Middle cerebral artery

References

1. Cecconi M, De Backer D, Antonelli M, et al. Consensus on circulatory shock and hemodynamic monitoring. Task force of the European Society of Intensive Care Medicine. Intensive Care Med. 2014;40(12):1795-1815. doi:10.1007/s00134-014-3525-z
2. Hamzaoui, O., Monnet, X. and Teboul, J.-L. (2016) Evolving concepts of hemodynamic monitoring for critically ill patients, Indian Journal of Critical Care Medicine. Available at: https://www.ijccm.org/abstractArticleContentBrowse/IJCCM/64/19/4/13711/abstractArticle/Article (Accessed: 29 August 2023).
3. Saugel B, Kouz K, Scheeren TWL, et al. Cardiac output estimation using pulse wave analysis- physiology , algorithms , and technologies : a narrative review. Br J Anaesth. Published online 2020. doi:10.1016/j.bja.2020.09.049
4. Lu Z, Mukkamala R. Continuous cardiac output monitoring in humans by invasive and noninvasive peripheral blood pressure waveform analysis. J Appl Physiol (1985). 2006;101(2):598-608. doi:10.1152/japplphysiol.01488.2005
5. Greiwe G, Peters V, Hapfelmeier A, Romagnoli S, Kubik M, Saugel B. Cardiac output estimation by multi-beat analysis of the radial arterial blood pressure waveform versus intermittent pulmonary artery thermodilution: a method comparison study in patients treated in the intensive care unit after off-pump coronary artery by. J Clin MonitComput. 2019;34(4):643-648. doi:10.1007/s10877-019-00374-0
6. Saugel B, Heeschen J, Hapfelmeier A, Romagnoli S, Greiwe G. Cardiac output estimation using multi-beat analysis of the radial arterial blood pressure waveform: a method comparison study in patients having off-pump coronary artery bypass surgery using intermittent pulmonary artery thermodilution as the reference me. J Clin MonitComput. 2020;34(4):649-654.
7. Khanna AK, Nosow L, Sands L, et al. Agreement between cardiac output estimation by multi-beat analysis of arterial blood pressure waveforms and continuous thermodilution in post cardiac surgery intensive care unit patients. J Clin MonitComput. Published online 2022. doi:10.1007/s10877-022-00924-z
8. Le Gall A, Vallée F, Joachim J, et al. Estimation of cardiac output variations induced by hemodynamic interventions using multi-beat analysis of arterial waveform: a comparative off-line

ISSN: 0975-3583,0976-2833 VOL15, ISSUE 12, 2024

study with transesophageal Doppler method during non-cardiac surgery. J Clin MonitComput. 2021;(0123456789). doi:10.1007/s10877-021-00679-z

9. Kee A, Kirchhoff B, Grigsby J, Proch K, Ji Y, Agashe H, Flynn BC. Prospective Evaluation of a Multibeat Analysis Cardiac Index Estimation in Patients With Cardiogenic Shock. J CardiothoracVascAnesth. 2023 Aug;37(8):1377-1381. doi: 10.1053/j.jvca.2023.04.003. Epub 2023 Apr 7. PMID: 37121841.

10. Lang et al. (2015). Recommendations for cardiac chamber quantification by echocardiography in adults: an update from the American Society of Echocardiography and the European Association of Cardiovascular Imaging. Eur Heart J Cardiovasc Imaging. 2015 Mar;16(3):233-70. doi: 10.1093/ehjci/jev014. Erratum in: Eur Heart J Cardiovasc Imaging. 2016 Apr;17(4):412. Erratum in: Eur Heart J Cardiovasc Imaging. 2016 Sep;17 (9):969. PMID: 25712077

11. Bland JM, Altman DG. Measuring agreement in method comparison studies. Stat Methods Med Res. 1999;8(2):135-160. doi:10.1177/096228029900800204

12. Critchley LAH, Critchley JAJH. A meta-analysis of studies using bias and precision statistics to compare cardiac output measurement techniques. J Clin MonitComput. 1999;15(2):85-91. doi:10.1023/A:1009982611386

13. Maeda T, Hattori K, Sumiyoshi M, Kanazawa H, Ohnishi Y. Accuracy and trending ability of the fourth-generation FloTrac/Vigileo System™ in patients undergoing abdominal aortic aneurysm surgery. J Anesth. 2018 Jun;32(3):387-393. doi: 10.1007/s00540-018-2491-y. Epub 2018 Apr 3. PMID: 29616345.

14. Crossingham IR, Nethercott DR, Columb MO. Comparing cardiac output monitors and defining agreement: A systematic review and meta-analysis. Journal of the Intensive Care Society. 2016;17(4):302-313. doi:10.1177/1751143716644457

15. Singer M, Deutschman CS, Seymour CW, Shankar-Hari M, Annane D, Bauer M, Bellomo R, Bernard GR, Chiche JD, Coopersmith CM, Hotchkiss RS. The third international consensus definitions for sepsis and septic shock (Sepsis-3). Jama. 2016 Feb 23;315(8):801-10.

16. Saugel B, Vincent J louis. Cardiac output monitoring: how to choose the optimal method for the individual patient. Curr Opin Crit Care. 2018;24(3):165-172. doi:10.1097/MCC.0000000000000492

ISSN: 0975-3583,0976-2833 VOL15, ISSUE 12, 2024

17. Zhang, Y. et al. (2019) Cardiac output measurements via echocardiography versus thermodilution: A systematic review and meta-analysis, PloS one. Available at: https://www.ncbi.nlm.nih.gov/pmc/articles/PMC6776392/

18. Wetterslev, M., Møller-Sørensen, H., Johansen, R.R. et al. Systematic review of cardiac output measurements by echocardiography vs. thermodilution: the techniques are not interchangeable. Intensive Care Med 42, 1223–1233 (2016). https://doi.org/10.1007/s00134-016-4258-y

19. Kulkarni, A.P. et al. (2022) ISCCM guidelines for hemodynamic monitoring in the critically ill, Indian journal of critical care medicine : peer-reviewed, official publication of Indian Society of Critical Care Medicine. Available at: https://www.ncbi.nlm.nih.gov/pmc/articles/PMC9989872/ (Accessed: 29 August 2023).

20. Montenij LJ, Buhre WF, Jansen JR, Kruitwagen CL, de Waal EE. Methodology of method comparison studies evaluating the validity of cardiac output monitors: a stepwise approach and checklist. Br J Anaesth. 2016 Jun;116(6):750-8. doi: 10.1093/bja/aew094. PMID: 27199309.

21. Saugel, Bernd, et al. "Cardiac output estimation using pulse wave analysis—physiology, algorithms, and technologies: A narrative review." British journal of anaesthesia 126.1 (2021): 67-76.

22. Peyton, Philip J., and Simon W. Chong. "Minimally invasive measurement of cardiac output during surgery and critical care: a meta-analysis of accuracy and precision." The Journal of the American Society of Anesthesiologists 113.5 (2010): 1220-1235.

23. Dorosz JL, Lezotte DC, Weitzenkamp DA, Allen LA, Salcedo EE. Performance of 3-dimensional echocardiography in measuring left ventricular volumes and ejection fraction: A systematic review and meta-analysis. J Am Coll Cardiol. 2012;59(20):1799-1808. doi:10.1016/j.jacc.2012.01.037