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ORIGINAL RESEARCH

Automatic assessment of left ventricular function for hemodynamic monitoring using artificial intelligence and transesophageal echocardiography

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Abstract

We have developed a method to automatically assess LV function by measuring mitral annular plane systolic excursion (MAPSE) using artificial intelligence and transesophageal echocardiography (autoMAPSE). Our aim was to evaluate autoMAPSE as an automatic tool for rapid and quantitative assessment of LV function in critical care patients. In this retrospective study, we studied 40 critical care patients immediately after cardiac surgery. First, we recorded a set of echocardiographic data, consisting of three consecutive beats of midesophageal two- and four-chamber views. We then altered the patient's hemodynamics by positioning them in anti-Trendelenburg and repeated the recordings. We measured MAPSE manually and used autoMAPSE in all available heartbeats and in four LV walls. To assess the agreement with manual measurements, we used a modified Bland–Altman analysis. To assess the precision of each method, we calculated the least significant change (LSC). Finally, to assess trending ability, we calculated the concordance rates using a four-quadrant plot. We found that autoMAPSE measured MAPSE in almost every set of two- and four-chamber views (feasibility 95%). It took less than a second to measure and average MAPSE over three heartbeats. AutoMAPSE had a low bias (0.4 mm) and acceptable limits of agreement (− 3.7 to 4.5 mm). AutoMAPSE was more precise than manual measurements if it averaged more heartbeats. AutoMAPSE had acceptable trending ability (concordance rate 81%) during hemodynamic alterations. In conclusion, autoMAPSE is feasible as an automatic tool for rapid and quantitative assessment of LV function, indicating its potential for hemodynamic monitoring.

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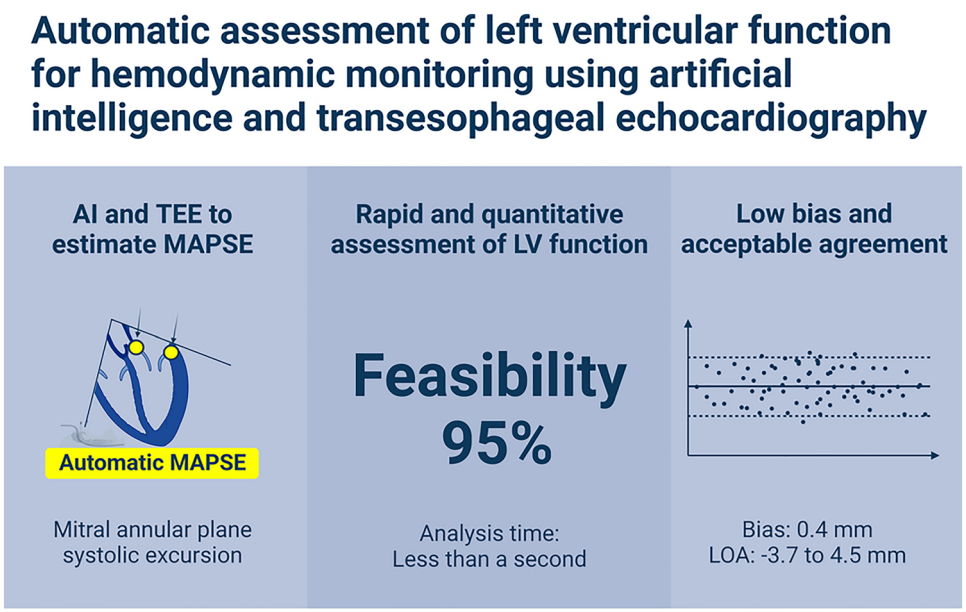
Graphical Abstract



Keywords Artificial intelligence · Circulatory failure · Critical care · Hemodynamic monitoring · Left ventricular function · Transesophageal echocardiography

Abbreviations

AI	Artificial intelligence
AutoMAPSE	Automatic measurement of mitral annular plane systolic excursion
CI	Confidence interval
LOA	Limits of agreement
LSC	Least significant change
LV	Left ventricle, left ventricular
MAPSE	Mitral annular plane systolic excursion
SD	Standard deviation
TEE	Transesophageal echocardiography
TTE	Transthoracic echocardiography
VTI	Velocity–time integral

1 Introduction

Rapid and accurate assessment of left ventricular (LV) function is crucial in management of cardiopulmonary failure in perioperative and critical care patients [1]. However, the clinical echocardiographic assessment of LV function is prone to variability [2, 3], which ultimately leads to imprecise measurements. When using imprecise methods for monitoring changes in LV function, real changes can only be detected when the change is large [4]. Such changes tend to occur late and are usually obvious or dramatic. For precise monitoring of LV function, there is a need for a rapid and quantitative method.

Recognition of this issue has triggered use of artificial intelligence (AI) in echocardiography, where rapid, quantitative assessments of LV function using AI are more precise than manual measurements [3, 5]. However, most of this AI-use is limited to transthoracic echocardiography (TTE), a method with a limited sonographic window in perioperative and critical care patients [6, 7]. To address this issue, we have developed a new tool for assessing LV function in these patients. Unlike solutions based on TTE, our method uses transesophageal echocardiography (TEE), which usually provides better image quality than TTE in these patients [6, 7]. Our method measures mitral annular plane systolic excursion (MAPSE) automatically by use of AI-guided image analysis (autoMAPSE) [8]. MAPSE reflects global LV longitudinal function [9] and has proven more valuable than LV ejection fraction in critical care patients [10]. AutoMAPSE was recently validated in cardiac patients [8], but its applicability in the critical care setting is yet to be evaluated.

Thus, our aim was to evaluate autoMAPSE as an automatic tool for rapid and quantitative assessment of LV function in critical care patients.

2 Methods

This is a retrospective analysis of anonymized data from an unpublished study (ClinicalTrials.gov ID: NCT04745845) that aims to investigate the impact of norepinephrine on ventriculoarterial coupling. The original study was approved by the regional ethics committee (REK number 2019/287) and all patients provided written informed consent prior to participating.

The original study included 40 patients scheduled for isolated coronary artery bypass grafting. We included anonymized data from all these 40 patients in this retrospective study. Because the original study investigated the impact of norepinephrine on ventriculoarterial coupling, patients with a poor Doppler signal from the LV outflow tract and those with a mean arterial pressure greater than 65 mmHg without norepinephrine were excluded. Importantly, three patients were also excluded from the original study due to poor definition of endocardial borders in TEE-images.

In the original study, the patients were stabilized after their arrival at the intensive care unit with muscle relaxants (cisatracurium 5–8 mg), sedation (propofol infusion 3–5 mg/kg/h and morphine 5–8 mg) and targeted a mean arterial pressure of 65 mmHg (norepinephrine infusion). The TEE-probe (6VT-D, GE Healthcare, Horten, Norway) was left in the esophagus after routine intraoperative use and reconnected to a Vivid S70 scanner (GE Healthcare, Horten, Norway).

To assess LV function during hemodynamic alterations, two sets of echocardiographic data were recorded in two different hemodynamic situations. Each set consisted of three consecutive heartbeats of midesophageal two- and four-chamber views, allowing us to obtain MAPSE from four walls: inferior and anterior wall (two-chamber view) and lateral and septal wall (four-chamber view). In addition, we recorded pulsed-wave Doppler signals from the LV outflow tract in either the transgastric long-axis view or the deep transgastric five-chamber view. The first set was recorded immediately after stabilization of the patients in the supine position, while the second set was recorded after reducing the patient's preload by positioning them in the anti-Trendelenburg position and after titration of the norepinephrine dose to target a mean arterial pressure of 65 mmHg. An experienced cardiac anesthesiologist, certified in TEE by the European Association of Cardiovascular Imaging, recorded all the images.

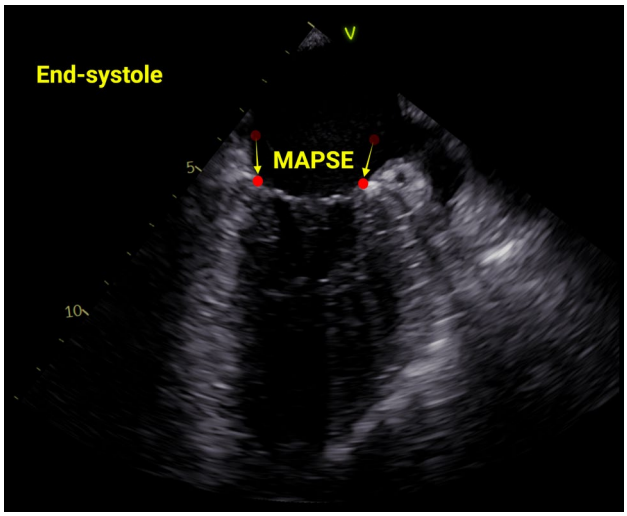


Fig. 1 Manual measurement of mitral annular systolic plane excursion (MAPSE). Red dots indicate the caliper placements on the mitral annulus in a midesophageal two-chamber view

2.1 Manual measurements of MAPSE

We measured MAPSE manually using EchoPAC software (version 204, GE healthcare, Horten, Norway). To do this, we identified the mitral annulus at the mitral valve hinge point on B-mode images of the two- and four-chamber views. Next, we used calipers to measure MAPSE as the distance from the highest to the lowest position (Fig. 1). If the image quality was suboptimal in end-diastole, we identified the annulus elsewhere in the cardiac cycle and followed the most hyperechogenic area at the insertion of mitral valve leaflets using a frame-by-frame analysis to end-diastole. For each wall, we measured three consecutive heartbeats. Finally, we reported the average MAPSE from the same wall and the same hemodynamic situation. To assess the time spent on measurements, we recorded the time it took to measure one recording (i.e., two walls, three beats) for 20 randomly selected patients.

To estimate the change in stroke volume, we traced the modal velocity of the pulsed-wave Doppler signal from the LV outflow tract in all patients. We then reported the velocity–time integral (VTI) as the average measurement of three consecutive heartbeats.

2.2 Automatic measurements of MAPSE

On the same echocardiographic images, we measured MAPSE automatically (autoMAPSE) using an off-line research computer. First, the mitral annulus was localized in each ultrasound frame using artificial intelligence (AI). This AI was designed as a convolutional neural network and trained on 10,302 annotated midesophageal two- and

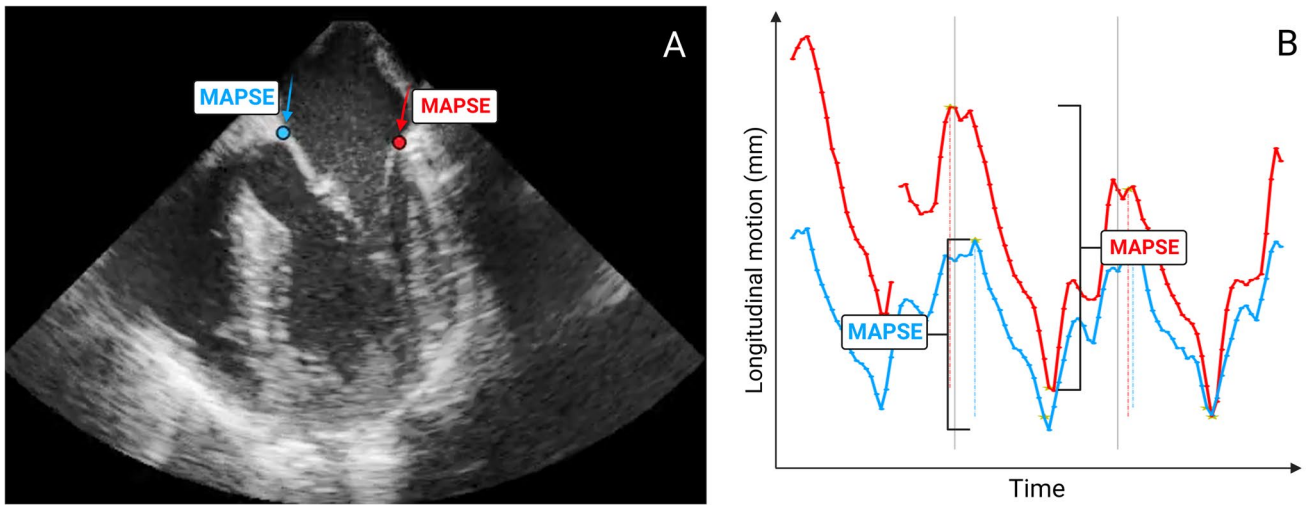


Fig. 2 Automatic measurement of mitral annular plane systolic excursion (MAPSE). **A**: The mitral annulus is detected automatically using artificial intelligence (red and blue dots). **B**: The longitudinal motion of the mitral annulus for the respective walls through time. For each heartbeat (vertical lines), MAPSE is the distance from the highest to the lowest position. Brackets, demonstrating the MAPSE of one heartbeat

four-chamber frames through supervised learning. The training data were obtained from various cardiac patients referred to the echocardiography laboratory for diagnostic TEE. The mitral annulus was annotated by two master students under guidance by an experienced clinical echocardiography researcher. To detect the annulus, the AI calculated the probability of its presence in each pixel of each ultrasound frame, i.e., a probability map. We then converted the probability maps from the AI into coordinate points that identify the mitral annulus on each ultrasound frame (Fig. 2A). As a quality check, the recording with the automatically detected mitral annulus was then presented back to us as a video (Supplementary video 1). Next, in order to obtain the longitudinal motion of the annulus for each heartbeat, we rotated the annular plane along its axis of movement, obtained the distance from the highest to the lowest position and applied a set of filtering algorithms to reject erroneous outliers for each specific heartbeat and wall. The filtering algorithms excluded the estimate if (1) the mitral annulus' frame-to-frame movement was more than 5 mm, (2) the mitral annulus was detected in less than 60% of the frames, and (3) if the highest position was not detected around the R-wave on the electrocardiogram. Rejecting erroneous outliers aims to reduce error, but at the cost of feasibility. We used autoMAPSE to obtain the MAPSE for all available heartbeats (Fig. 2B). Finally, we reported the average MAPSE from the same wall and the same hemodynamic situation. More technical details about the AI are given elsewhere [8].

We defined autoMAPSE as overall feasible if it estimated LV function from one set of echocardiographic data, in other words: MAPSE from at least one beat in at least one LV wall during a specific hemodynamic situation. The feasibility of each individual wall was the proportion of at least one estimate from that specific wall during that specific hemodynamic situation.

Table 1 Patient characteristics (N = 40)

Variables	Total (N = 40)
Age (years)	68 ± 8.6
Body mass index (kg/m^2)	30 ± 4.8
Male/female (n)	35/5
Diabetes (n, %)	13 (33)
Preoperative ejection fraction < 50% (n, %)	7 (18)
Postoperative ejection fraction (%)	52 ± 12
History of myocardial infarction (n, %)	13 (33)
History of hypertension (n, %)	21 (53)
Cerebrovascular disease (n, %)	2 (5)
Chronic lung disease (n, %)	2 (5)
Norepinephrine, supine (mcg/kg/min)	0.02 ± 0.03
Norepinephrine, anti-Trendelenburg (mcg/kg/min)	0.04 ± 0.04

Values are mean ± SD

2.3 Statistical analysis

Our main outcomes were the bias, limits of agreement (LOA), precision and trending ability of autoMAPSE compared to manual measurements. We report descriptive statistics as mean ± standard deviation (SD). We analyzed the changes between hemodynamic alterations using paired t-test for normally distributed data and Wilcoxon signed-rank test

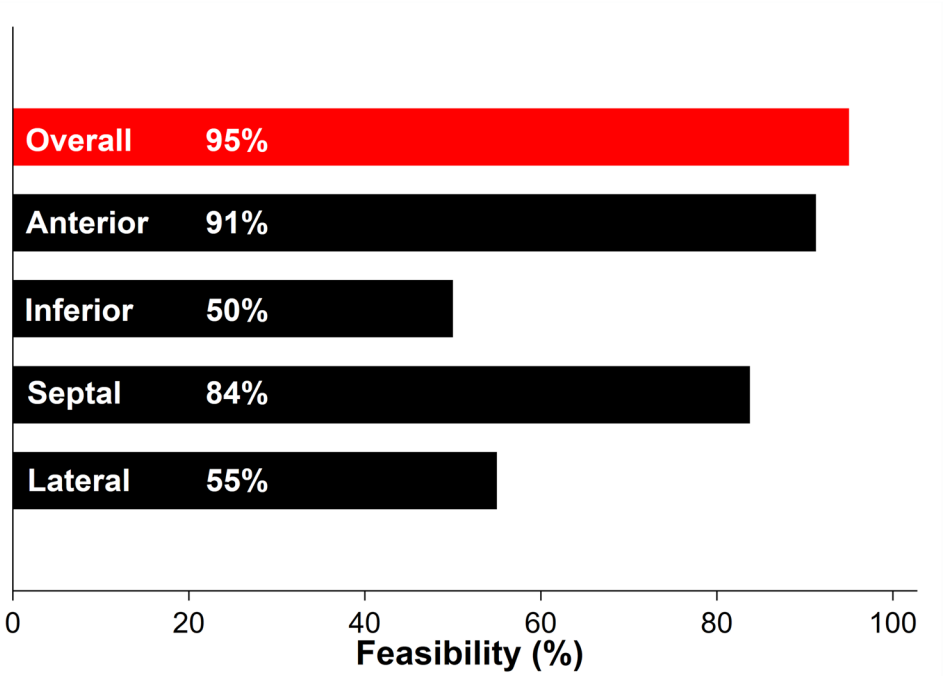


Fig. 3 Overall feasibility of automatic measurement of mitral annular plane systolic excursion and feasibility for each individual wall

for non-normal distributions. For this retrospective study, we did not perform any sample size calculation.

To assess the bias and LOA of autoMAPSE and manual measurements, we used the Bland–Altman analysis [11]. Because we measured each patient's MAPSE in four LV walls, at two hemodynamic situations, and in up to three heartbeats in each situation, the measurements were not independent. Unless adjusted for, this dependency will cause the LOA to be underestimated using the conventional Bland–Altman analysis [12, 13]. Therefore, we modified the Bland–Altman analysis using a linear mixed effects model with restricted maximum likelihood, where the fixed effects were *measurement method* and *patient* and the random effects were *measurement method-patient interaction* and *patient-MAPSE interaction* [13]. We verified homogeneity of variance by fitting a variance function

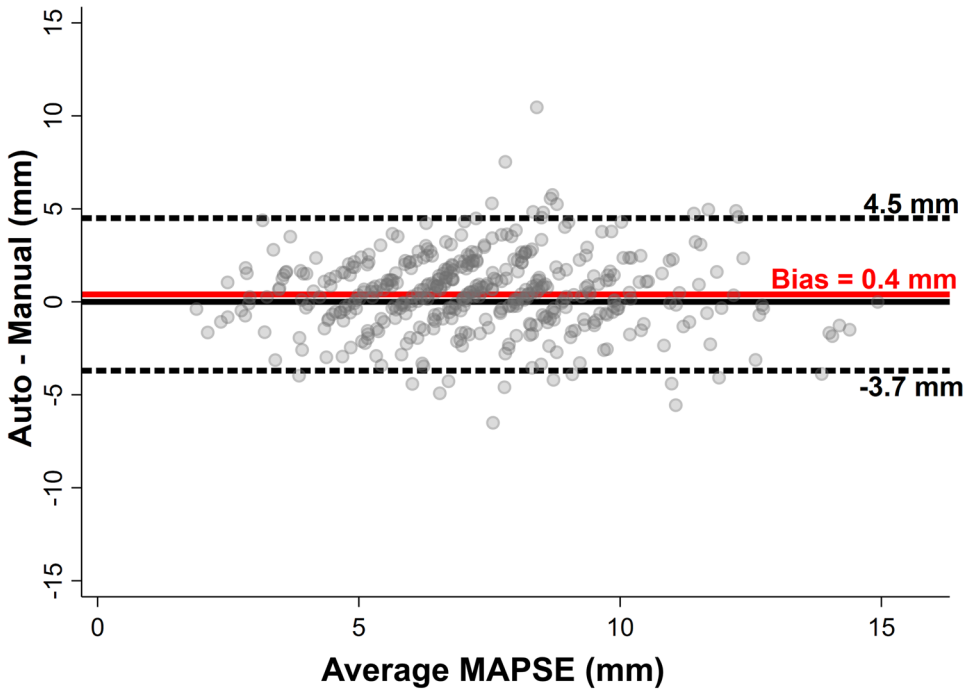


Fig. 4 Bland–Altman plot comparing automatic measurements of mitral annular plane systolic excursion with manual measurements. Data are pooled from four walls and two hemodynamic situations. Each point is a measurement from one wall and one heartbeat. Red line, bias; dashed lines, 95% limits of agreement that are adjusted for within-patient dependency; MAPSE, mitral annular plane systolic excursion

for the residuals. Acceptable agreement is commonly set as the LOA for interobserver variability when validating AI in echocardiography [5, 14–16]. We chose a similar approach, and defined acceptable agreement as the LOA for interobserver variability of the manual measurements of MAPSE between two independent echocardiographers from a previous study (LOA -4.7 to 3.0 mm, range 7.7 mm) [8]. In addition, we assessed our own intra- and interobserver variability of the manual measurements in this present study. The original observer and a second observer reanalyzed 20 randomly selected patients 6 months later, and we used the same linear mixed effects model to obtain the LOA. For the intraobserver variability of autoMAPSE, we reanalyzed the entire echocardiographic dataset.

To assess the precision of each method, we used the residual SD for autoMAPSE and manual measurements from the linear mixed effects model already described. We reported the precision as the least significant change (LSC) for one, two and three measurements using the formula: $\mathrm{LSC} = \sqrt{2} \times 1.96 \times \mathrm{SD}/\sqrt{n}$ measurements [4, 13].

Table 2 Least significant change, calculated for each number of measurements

Measurement method	One measurement (95% CI)	Two measurements (95% CI)	Three measurements (95% CI)
AutoMAPSE (mm)	4.3 (3.9–4.8)	3.1 (2.8–3.4)	2.5 (2.3–2.8)
Manual measurement (mm)	3.5 (3.0–4.0)	2.5 (2.2–2.8)	2.0 (1.8–2.3)

Least significant change for one, two and three measurements by mixed linear model with restricted maximum likelihood. AutoMAPSE, automatic measurement of mitral annular plane systolic excursion; CI, confidence interval

To assess the trending ability of autoMAPSE, we used a four-quadrant plot and reported the concordance rate

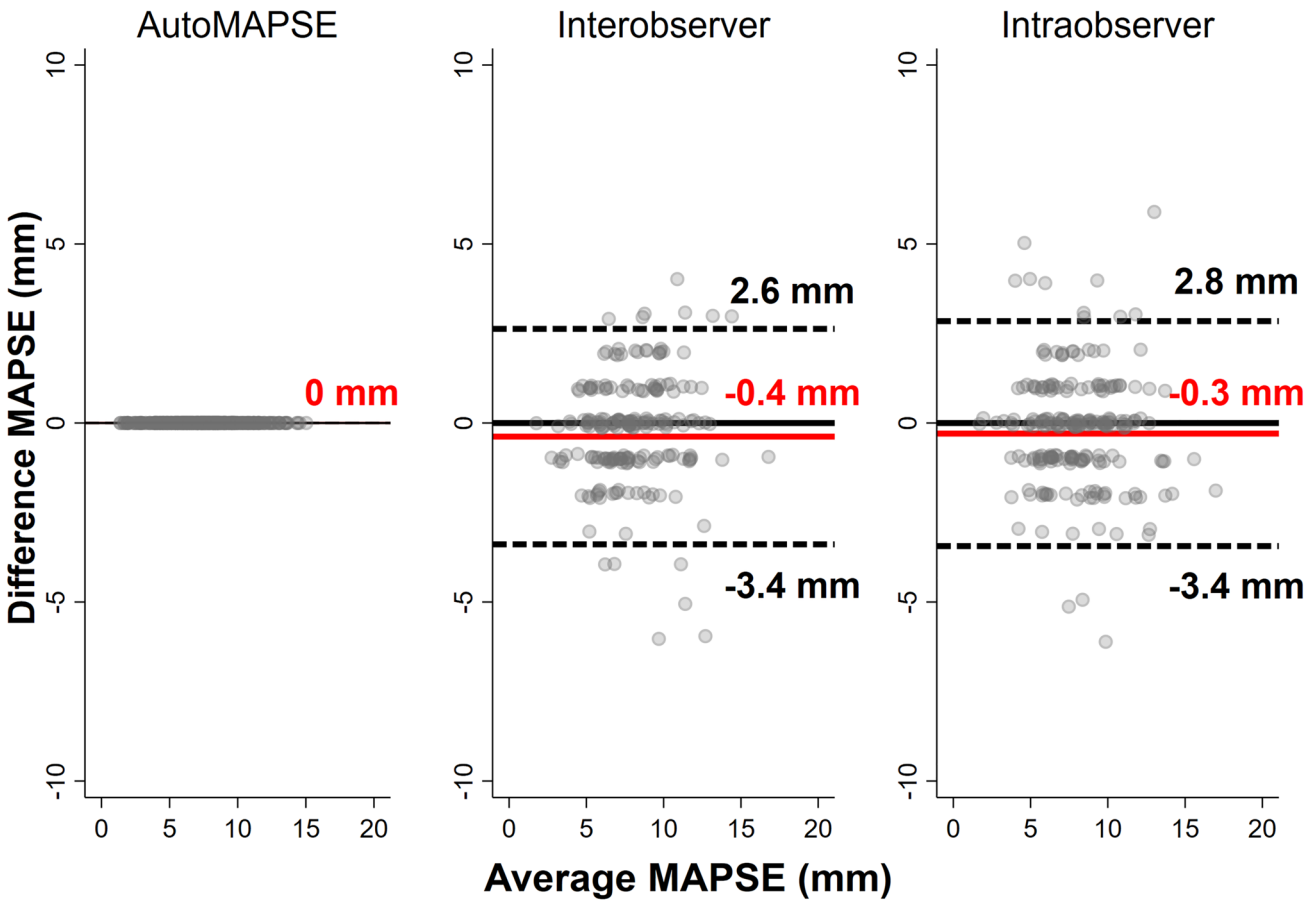


Fig. 5 Bland–Altman plots of intra- and interobserver variability. **Left**: Intraobserver variability for autoMAPSE on all the echocardiographic data. **Middle**: Interobserver variability for manual measurements on 20 patients. **Right**: Intraobserver variability for manual measurements on 20 patients. Each point is a measurement from one wall and one heartbeat. Red line, bias; dashed lines, 95% limits of agreement; autoMAPSE, automatic measurement of mitral annular plane systolic excursion; MAPSE, mitral annular plane systolic excursion

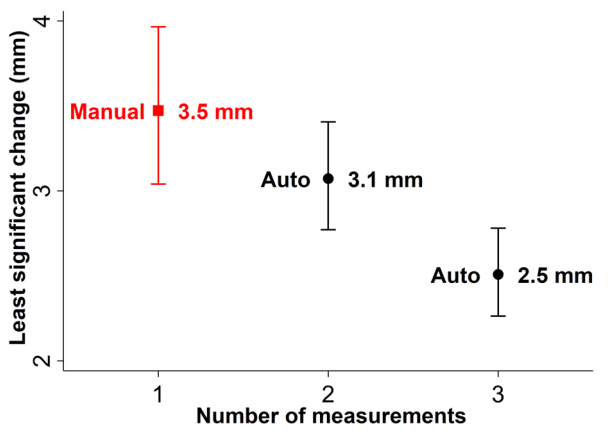


Fig. 6 Precision of each method, reported as least significant change. Lower least significant change means better precision. Black plots are automatic measurements; the red plot is one manual measurement. Dots are the mean; brackets are 95% confidence interval; auto, automatic measurement of mitral annular plane systolic excursion

Table 3 Mitral annular plane systolic excursion for supine and anti-Trendelenburg position with a mean arterial pressure of 65 mmHg

	Supine	Anti-Trendelenburg
AutoMAPSE (mm)		
Anterior	7.9 ± 1.5	5.8 ± 2.1*
Septal	7.2 ± 2.3	6.9 ± 2.4
Inferior	8.6 ± 2.2	7.3 ± 2.5*
Lateral	9.1 ± 2.8	8.0 ± 2.6
Manual MAPSE (mm)		
Anterior	7.4 ± 1.7	6.4 ± 1.8*
Septal	6.2 ± 1.5	5.4 ± 1.7*
Inferior	7.4 ± 2.2	6.2 ± 2.1*
Lateral	9.1 ± 2.8	7.5 ± 2.5*
Velocity–time integral (cm)	15.9 ± 3.5	13.5 ± 2.9*
Heart rate (beats/min)	71 ± 9	73 ± 11

Hemodynamic and echocardiographic measurements for supine and anti-Trendelenburg with a mean arterial pressure of 65 mmHg. Values are mean ± SD. MAPSE, mitral annular plane systolic excursion; AutoMAPSE, automatic measurement of mitral annular plane systolic excursion. *Indicates statistical significance (P-value < 0.05)

[17]. Measurements were concordant if they changed in the same direction. We defined 80% concordance rate as acceptable trending ability, and 95% concordance rate as excellent. When comparing changes in MAPSE, we set the central exclusion zone as the LSC for manual measurements of MAPSE; when comparing against changes in VTI, we set the exclusion zone as 15% change in VTI [17].

We fitted the variance function using the package *nlme* in software R (version 4.2.2), otherwise we used the *mixed* command in Stata 17.0 (StataCorp LLC).

3 Results

We analyzed a total of 80 sets of midesophageal two- and four-chamber views in 40 patients (Table 1). AutoMAPSE estimated LV function in almost every set, with an overall feasibility of 95% (Fig. 3). Of the individual walls, the anterior and septal walls were the most feasible (91% and 84%, respectively, Fig. 3). No patients were excluded from this retrospective analysis. On average, autoMAPSE measured three heartbeats in less than a second (0.72 ± 0.21 s). In comparison, manual measurements of one recording (i.e., two walls, three beats) took on average more than two minutes (133 ± 33 s). There were no complications of TEE and no cases of significant arrythmias.

The bias between autoMAPSE and manual measurements was low (0.4 mm), and the agreement was judges as acceptable (LOA -3.7 to 4.5 mm, range 8.2 mm, Fig. 4). Visual inspection of the Bland–Altman plot also showed a constant variance across the range of MAPSE. In comparison, the inter- and intraobserver variability of manual measurements in this study was narrower, while autoMAPSE, by design, had no intraobserver variability (Fig. 5).

Although manual measurements were more precise than autoMAPSE when comparing the same number of measurements, autoMAPSE was more precise when averaging one or more measurement (Table 2). In other words, the average of two or more autoMAPSE measurements was more precise than the clinical practice of one manual measurement (Fig. 6).

AutoMAPSE responded to hemodynamic alterations (Table 3). AutoMAPSE had acceptable trending ability when compared to manual measurements of MAPSE (Fig. 7A). Changes in MAPSE also tracked the changes in LV outflow tract VTI (Fig. 7B, C).

4 Discussion

This study shows that autoMAPSE is feasible as an automatic tool for rapid and quantitative assessment of LV function in critical care patients. Three important results support this finding. First, autoMAPSE was highly feasible. Second, compared with manual measurements, autoMAPSE had a low bias and was more precise if it averaged more measurements. Third, autoMAPSE had acceptable trending ability during hemodynamic alterations. This simple addition to the echocardiographic repertoire can be useful for clinicians managing cardiopulmonary failure. Clinical acceptance is likely since clinicians can benefit from autoMAPSE without compromising any of the established advantages of critical care echocardiography.

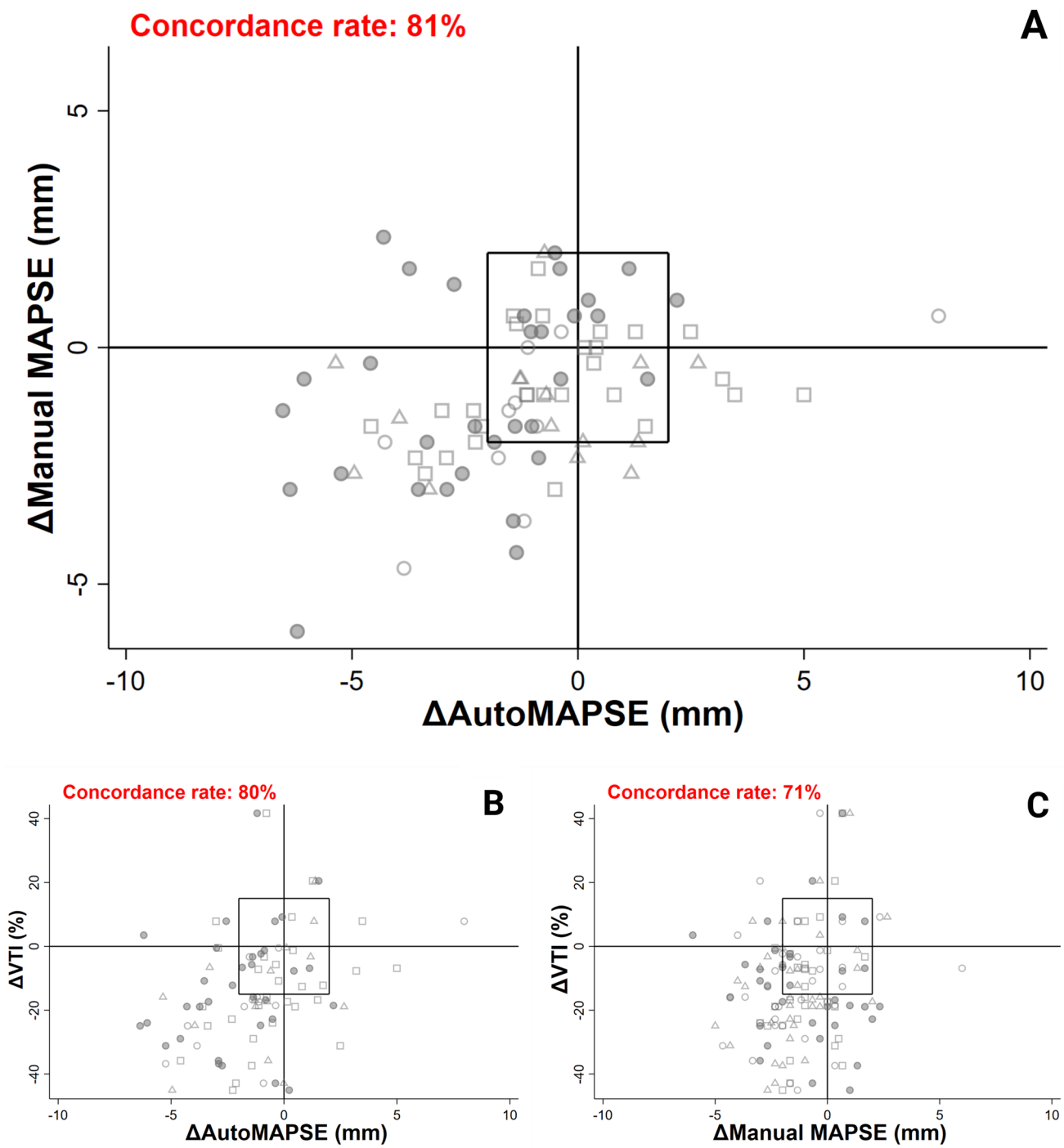


Fig. 7 Changes in MAPSE during hemodynamic alterations. Each point is the average measurement of up to three heartbeats. **A** Changes in autoMAPSE against changes in manual MAPSE. **B** Changes in autoMAPSE against changes in VTI. **C** Changes in manual MAPSE against changes in VTI. MAPSE, mitral annular plane systolic excursion; autoMAPSE, automatic measurement of mitral annular plane systolic excursion VTI, velocity–time integral. Filled circles, anterior wall; open circles, inferior wall; triangles, lateral wall; squares, septal wall

4.1 The importance of precision

Our most important finding regarding autoMAPSE as a tool for future hemodynamic monitoring is its ability to rapidly obtain and average the MAPSE of all available heartbeats. This averaging of multiple measurements increases the precision of any method, but despite guidelines suggesting that we manually measure and average three heartbeats [18], the

common clinical practice is to assess LV function either visually or by measuring one heartbeat. Both of these practices are prone to error, which leads to imprecision [2, 3]. Instantaneous averaging of multiple measurements increases the precision of autoMAPSE to a level that surpasses clinical practice. Using AI also eliminates intraobserver variability. The result is that we can detect smaller changes in LV function. In our study, the LSC for the average of three heartbeats was still quite high (2.0 to 2.5 mm). Thus, to detect even smaller changes in LV function, even more measurements must be averaged. This is a task best suited for an automated tool.

The limitations of the retrospective study design reveal the crucial importance of a method's precision. First, although the overall feasibility of autoMAPSE was 95%, not all patients nor all walls had more than one valid autoMAPSE measurement per hemodynamic situation. Second, as MAPSE is preload dependent, we can expect physiologic variation in MAPSE within a respiratory cycle. Solving this issue requires us to average the MAPSE of all heartbeats throughout a respiratory cycle; the average of three heartbeats is not enough. Combined, these two issues reduced the precision of autoMAPSE in some of our study subjects. This may explain why autoMAPSE detected a statistically significant decrease in MAPSE in only two walls. Due to the retrospective design, it was impossible to increase the number of heartbeats for autoMAPSE to measure. Again, this is not a limitation in the real-world, where we are free to present autoMAPSE with as many heartbeats as we like, thereby easily improving its ability to detect smaller changes.

4.2 Acceptable agreement

When judging the agreement of a new method, the reference method's precision is often overlooked [4] and sometimes the reference method is assumed to be the gold standard. We assessed the precision of our reference method and were reminded that our manual measurements contained human error and that our reference method was far from being a gold standard (Table 2, Fig. 6). This is expected, but confusion can arise when the imprecise human measurements simultaneously serve as the method to be improved *and* as the reference method. An imprecise reference method acts as a moving target for the new method, causing the LOA to widen, but without affecting the bias or the constancy of variance [4, 11, 19]. If we only focus on the wide LOA, we may erroneously discard the new method despite low bias, constant variance and other advantageous features [4, 11, 19]. This is a common problem when validating AI in echocardiography, and a common solution is to define acceptable agreement as the LOA for interobserver variability [5, 8, 14–16]. A reason for using the interobserver variability is that this metric is closer to the variability encountered in a real-world situation. During patient follow-up, the patient is often exposed to different operators. Using the interobserver variability evaluates autoMAPSE as any other operator. Using this approach, we found that autoMAPSE had acceptable agreement with manual measurements since its LOA (− 3.7 to 4.5 mm) is in the clinical range of the LOA of interobserver variability between two independent echocardiographers using the same manual method (− 4.7 to 3.0 mm) [8]. Other evidence supporting this interpretation is the low bias and the constancy of variance across the range of MAPSE (Fig. 4).

4.3 Clinical implications

For monitoring purposes in perioperative and critical care patients, our study reveals several advantageous features of autoMAPSE. First, autoMAPSE performed similarly in patients after cardiac surgery compared to a previous study involving cardiac patients [8]. Importantly, this finding was without further training data and without excluding any patients. Furthermore, MAPSE is a practical and robust metric of LV longitudinal function in critical care patients [10, 20–22]. In TEE, physical limitations to ultrasound, such as mitral annular calcifications, valve prostheses and distance of the apical segments of the LV, all limit ultrasound penetration and, thus, reduces the image quality needed for estimating LV ejection fraction and global longitudinal strain. These physical limitations apply less to MAPSE, which exploits the distinct mitral annulus close to the TEE-probe. Our study shows that this advantage allows excellent feasibility (Fig. 3).

Although our criteria for feasibility only required MAPSE to be obtained from one LV wall, several reports suggests that MAPSE from one wall may be sufficient for monitoring global LV function. Evidence from cardiac patients suggests that single-wall MAPSE using cardiac magnetic resonance imaging is sufficient in predicting outcomes [23]. Two studies using cardiac magnetic resonance imaging and one using echocardiography suggests that MAPSE is globally depressed after myocardial infarction, even in walls remote to the ischemic region [24–26]. Experimental data using cardiac magnetic resonance imaging shows the same [27]. This indicates that MAPSE from a single wall does not reflect regional LV function of that wall, but rather that the MAPSE of any wall reflects global LV function. Various methods for measuring MAPSE have repeatedly demonstrated significant clinical value [9, 10, 20, 22, 23, 28–30]. Interestingly, when compared head-to-head using cardiac magnetic resonance imaging, MAPSE had even better prognostic ability than both global longitudinal strain and LV ejection fraction in a cardiological cohort [28]. In sum, serial assessment of MAPSE from the same wall could serve as automatic monitoring of LV function in the future.

4.4 Limitations

The small sample size and retrospective design are important limitations of this study. Furthermore, our study has some additional limitations. First, we recognize that TEE may cause complications. However, they are usually self-limiting, and severe bleeding and gastrointestinal perforation are very rare [31–34]. Second, the current version of autoMAPSE does not adjust for post-systolic shortening. Finally, the present study has not evaluated autoMAPSE for continuous hemodynamic monitoring. The images were analyzed off-line, and not in real-time. Also, for the method to be truly automatic, the probe must also be in passive position and imaging must be hands-free. This was not the case in our study. A passive probe is also important to reduce the risk of TEE-related complications [35]. However, our findings demonstrate that autoMAPSE is feasible in a critical care setting. The next step is to validate autoMAPSE prospectively in a real-time, continuous monitoring situation over time.

5 Conclusion

We found that autoMAPSE is highly feasible as an automatic tool for rapid and quantitative assessment of LV function in critical care patients. Compared to manual measurements, autoMAPSE had a low bias and better precision when averaging more heartbeats. Finally, autoMAPSE reflected hemodynamic alterations.

Supplementary Information The online version contains supplementary material available at https://doi.org/10.1007/s10877-023-01118-x.

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Author contributions Conceptualization: JY, AAT, EARB, BG, IKG, GK, SA; Data curation: JY, AAT, HMF, ES; Formal analysis: JY, AAT, HMF, ES, EARB; Funding acquisition: AR, IKG, GK, SA; Investigation: JY, AAT, HMF, AR, IKG; Methodology: JY, AAT, HMF, ES, EARB, BG, AR, IKG, GK, SA; Project administration: JY, AR, IKG, GK, SA; Resources: JY, AAT, HMF, AR, IKG; Software: JY, AAT, EARB, BG, GK, SA; Supervision: AR, IKG, GK, SA; Validation: JY, EARB; Visualization: JY, AAT, ES; Writing – original draft: JY, SA; Writing – review and editing: JY, AAT, HMF, ES, EARB, BG, AR, IKG, GK, SA. All authors approved the final manuscript.

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Declarations

Competing interests BG and EARB hold positions at Centre for Innovative Ultrasound Solutions (CIUS) – a Norwegian Research Council center for research-based innovation, where GE HealthCare, Horten, Norway, is one of the industrial partners. The other authors have no competing interests to declare that are relevant to this manuscript.

Ethical approval The regional ethics committee (REK number 2019/287) approved the original and all patients provided written informed consent prior to participating. The regional ethics committee confirmed that no ethical approval was needed for analysis of anonymized data for this current study.

Statement of human rights The original study was approved by the regional ethics committee (REK number 2019/287) in line with the principles of the Declaration of Helsinki.

Statement on welfare of animals Not applicable.

Informed consent Informed consent was obtained from all the patients. This report did not contain any personal information that could lead to patient identification.

Consent to participate All patients provided written informed consent prior to participating.

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