

ORIGINAL ARTICLE

## Study on Image Acquisition of Transthoracic Echocardiography in Mechanically Ventilated ICU Patients

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**Key words:** critically ill; transthoracic echocardiography; medical image

**Objective** This study aimed to determine which parameters in transthoracic echocardiography (TTE) are more likely to be affected when applied in a critical care setting with mechanical ventilation.

**Methods** Ninety mechanically ventilated ICU patients were enrolled into the study group. The control group consisted of 90 patients who underwent interventional therapy. All patients had bedside TTE for parametric measurements including the right ventricular size, septal kinetics and left ventricular ejection fraction (LVEF) by eyeballing (visual assessment), the tricuspid annular plane systolic excursion (TAPSE), mitral annular plane systolic excursion (MAPSE) by M-mode sonography, the right ventricular outflow tract velocity-time integral (RVOT VTI) and left ventricular outflow tract velocity-time integral (LVOT VTI) by pulse-Doppler, the right ventricular fraction of area change (FAC) and left ventricular ejection fraction (LVEF Simpson) by endocardium tracing. We compared the differences in the frequency of optimal image acquisition in assessments of these parameters between the two groups, as well as the differences in acquisition rates of parameter measurements in ventilated ICU patients.

**Results** There were significantly fewer patients in the study group than in the control group who had optimal images acquisitions for parameter assessments with M-mode method, pulse Doppler method and endocardium-tracing method ( $P<0.05$ ); no significant difference was observed in the number of patients with optimal images for RV eyeballing and LVEF eyeballing between the two groups. In the study group, significantly fewer optimal images were acquired for FAC than for TAPSE (22.2% vs. 72.2%,  $\chi^2=45.139$ ,  $P<0.001$ ) and RVOT VTI (22.2%

vs. 71.1%,  $\chi^2=43.214$ ,  $P<0.001$ ); there were also fewer optimal images acquired for LVEF Simpson than for MAPSE (37.8% vs. 84.4%,  $\chi^2=41.236$ ,  $P<0.001$ ) and LVOT VTI (37.8% vs. 85.6%,  $\chi^2=43.455$ ,  $P<0.001$ ).

**Conclusions** Images acquisition of optimal TTE images tend to be difficult in mechanically ventilated ICU patients, but eyeballing method for functional evaluation could be an alternative method. For quantitative parameters measurements, M-mode based longitudinal function evaluation and pulse Doppler-based VTI were superior to the endocardium-tracing based parameter assessments.

**E**CHOCARDIOGRAPHY is a valuable tool for management of hemodynamic instability in intensive care unit (ICU). Early echocardiographies allow clinicians to interpret the state of a shock and to develop an effective strategy for therapy. Skills of transthoracic echocardiography (TTE) at bedside are key elements in intensivists' training.<sup>[1]</sup>

Several studies have demonstrated that it is completely feasible for non-cardiologists to master the skills of hemodynamic assessment of heart function through echocardiographic examination.<sup>[2,3]</sup> Left ventricular systolic function is of great importance, whereas the right heart function should also be assessed through qualitative and quantitative methods.<sup>[4]</sup>

However, image acquisition is often much difficult in critically ill patients than non-ICU patients due to patient position, positive ventilation, surgical incisions and drainage, etc. Parasternal view, apical view and subcostal view are the common TTE examination sites. Jensen MB *et al.* noted that in only 34% of intensive care patients, usable images could be acquired from all the three sites.<sup>[5]</sup> However, to our knowledge, parameters that are more easily affected in the setting of critical care have not been investigated by far.

Our study aimed to determine the ratio of adequate image acquisition in mechanically ventilated ICU patients, and to investigate which echocardiographic parameters are more likely to be affected.

## PATIENTS AND METHODS

### Study population

This prospective observational study was conducted at a tertiary hospital, following the Declaration of Helsinki and was approved by the ethics committee of the Peking Union Medical College Hospital. Written informed consents were obtained from all patients. Critically ill patients admitted to the ICU from July 1st, 2016 to September 1st, 2016 who received mechanical ventilation were enrolled as the study group. All enrolled

patients received a transthoracic echocardiographic evaluation within 6 hours of admission. Physiologic parameters, including hemodynamic data and current vasoactive medications, were recorded at the time of echocardiography. The control group consisted of patients from interventional ward for scheduled interventional therapy. They were selected basing on 1:1 matching with patients in the study group on age (difference within 5 years old) and BMI (difference within 3 kg/m<sup>2</sup>), and also received transthoracic echocardiographic evaluation within 6 hours of ICU admission as the study group.

### Echocardiography

Heart rate and blood pressure were obtained from a monitor at the onset of examination. Echocardiograms were performed using an echocardiographer (Sonosite, M-Turbo, California, USA) with a 2.5 MHz phased array probe. Patients lied at the semi-left lateral position during examination unless there was an absolute contraindication for this position. Parasternal view, subcostal view and apical view of echocardiography were all tried in all enrolled patients unless the site was not accessible due to surgical incision or drainage tube.

The examinations were performed by two fellowship-trained intensivists with more than 5 years of experience in sonography and at least 200 examinations of annual performances, which ensured their competence in this specialty.<sup>[6]</sup> They made the judgement whether the image quality was adequate for the assessment of intended parameters. Both were blinded to the study protocol when performing echocardiography.

The image quality was appraised in 3 steps:

- 1) They tried to obtain images from all the three sites and determine if the basic structures, such as endocardium of both ventricles, mitral and tricuspid ring, were discernible according to the image quality rating scale of the Emergency Ultrasound Standard Reporting Guideline (**Table 1**).<sup>[7]</sup>
- 2) If images score from any site was less than

or equal to 3, they determine whether the image was good enough for eyeballing methods.

3) If image score was equal to or higher than 3, they made the quantitative measurement to achieve the specific parameters.

The video clips of parasternal longitudinal and short-axis plane, apical four-chamber and two-chamber plane, subcostal four-chamber and short axis plane were stored and so were the measurements of each parameter. Another cardiologist who have 10 years experience of echocardiography double-checked all images before making a final judgement.

### Parameters and measurement methods

Visual assessment of right ventricular (RV eyeballing) on size and septal kinetics included whether the right ventricle is enlarged and whether there is septal paradoxical movement.<sup>[4]</sup> Visual assessment of left ventricular function (LVEF eyeballing) included ejection fraction by eyeballing, which was reported to correlate well with quantitative measurement.<sup>[8]</sup>

M-mode longitudinal function parameters included mitral annular plane systolic excursion (MAPSE) and tricuspid annular plane systolic excursion (TAPSE). They were taken from a apical 4-chamber view with cursor at the left and right sites of atrioventricular rings.

The velocity-time integral (VTI) of left ventricular outflow tract (LVOT) was assessed using pulsed Doppler by putting the sample volume at LVOT approximately 0.5 cm below the aortic valve,<sup>[9]</sup> and the VTI of right ventricular outflow tract (RVOT) was obtained on the short-axis plane of aortic root either from the parasternal view or from subcostal view where the RVOT can be readily displayed.

**Table 1.** The image quality grading scale

| Grading score | Definitions                                                                                                                |
|---------------|----------------------------------------------------------------------------------------------------------------------------|
| 1             | No recognizable structures, no objective data can be gathered                                                              |
| 2             | Minimally recognizable structures but insufficient for diagnosis                                                           |
| 3             | Minimal criteria met for diagnosis, recognizable structures but with some technical or other flaws                         |
| 4             | Minimal criteria met for diagnosis, all structures displayed well and diagnosis easily supported                           |
| 5             | Minimal criteria met for diagnosis, all structures displayed in excellent image quality and diagnosis completely supported |

Endocardium-tracing based ventricular function assessment included measurement, of LVEF and RV FAC by Simpson's biplane method. The RV FAC was measured by tracing the RV endocardium both in systole and diastole from the annulus to the apex along the free wall, and then back to the annulus along the interventricular septum.<sup>[4,10]</sup>

### Statistical analysis

Statistical analysis was performed using SPSS (Version 13.0, SPSS Inc., Chicago, Illinois). Continuous data were described as mean and standard deviation and were compared with student's *t*-test, Mann-Whitney test, or One-way ANOVA. Categorical variables were described as number and percentage and were compared with Chi-square test or Fisher exact test. Statistical significance was determined when  $P < 0.05$ .

## RESULTS

### General characteristics of patients

A total of 120 consecutive patients admitted to the ICU were screened for enrolment. Five were excluded due to lack of informed consents, and 25 were excluded for no mechanical ventilation. Ultimately, 90 patients were enrolled in the study group. Ninety non-ICU patients from the interventional ward were selected as the control group by 1:1 matching on age and BMI.

Patients in the study group were admitted to ICU for shock (15, 16.7%), respiratory failure (21, 23.3%) and high-risk surgeries (54, 60%), such as abdominal, cardiac, thoracic, orthopaedic, and urinary surgeries. There were 25 (27.8%) patients with an epigastric surgical wound, and 5 (5.6%) patients with a subcostal drainage tube. All patients in the study group were on mechanical ventilation, the mean of PEEP was  $5.4 \pm 1.3$  cmH<sub>2</sub>O, and the mean of plateau pressure was  $14.1 \pm 3.5$  cmH<sub>2</sub>O. No patients in the control group were on mechanical ventilation.

Comparison of the clinical characteristics between the two group were presented in **Table 2**. The study group had higher Acute Physiology and Chronic Health Evaluation (APACHE) II score ( $14.5$  vs.  $9.7$ ,  $P < 0.001$ ). There were no differences in age, BMI, and sex between the two groups. No difference in comorbidity was found between the two groups in terms of hypertension, coronary arterial disease, diabetes mellitus, chronic renal failure, and chronic obstructive pulmonary disease.

### Echocardiographic parametric assessments and image acquisitions

Compared to the control group, fewer patients with mechanical ventilation achieved optimal image acquisition for measuring parameters of TAPSE ( $X^2=10.724$ ,  $P<0.01$ ), MAPSE ( $X^2=9.878$ ,  $P<0.01$ ), RVOT VTI ( $X^2=6.538$ ,  $P<0.05$ ), LVOT VTI ( $X^2=8.800$ ,  $P<0.01$ ), FAC ( $X^2=32.67$ ,  $P<0.001$ ), and LVEF ( $X^2=35.051$ ,  $P<0.001$ ). No significant difference were observed in the function evaluation by eyeballing for RV ( $X^2=3.183$ ,  $P>0.05$ ) and LVET ( $X^2=2.421$ ,  $P>0.05$ ) (**Table 3**). In the study group, optimal image acquisitions for

FAC were significantly less achieved than for TAPSE (22.2% vs. 72.2%,  $X^2=45.139$ ,  $P<0.001$ ) and RVOT VTI (22.2% vs. 71.1%,  $X^2=43.214$ ,  $P<0.001$ ); optimal image acquisitions for LVEF Simpson were significantly less achieved than for MAPSE (37.8% vs. 84.4%,  $X^2=41.236$ ,  $P<0.001$ ) and LVOT VTI (37.8% vs. 85.6%,  $X^2=43.455$ ,  $P=0.001$ ) (**Table 3**).

## DISCUSSION

In the present study, we found that in ICU patients, echocardiography tended to have less chance

**Table 2.** General characteristics of the patients in the study group and the control group<sup>§</sup>

| Categories          | Study group (n=90) | Control group (n=90) | t/ $X^2$ value | P value |
|---------------------|--------------------|----------------------|----------------|---------|
| Age(y/o, mean±SD)   | 58.7±15.3          | 55.8±15.5            | 1.538          | 0.215   |
| Sex-male [n(%)]     | 41(45.6)           | 48(53.3)             | 1.089          | 0.371   |
| BMI                 | 23.2±3.2           | 22.7±3.3             | 1.257          | 0.367   |
| APACHE II score     | 14.5±6.4           | 9.7±3.2              | 7.706          | 0.000   |
| Comorbidities       |                    |                      |                |         |
| HTN [n(%)]          | 37(41.1)           | 26(28.9)             | 2.955          | 0.086   |
| CAD [n(%)]          | 20(22.2)           | 14(15.6)             | 1.305          | 0.253   |
| DM [n(%)]           | 19(21.1)           | 17(18.9)             | 0.139          | 0.709   |
| CRF [n(%)]          | 7(7.8)             | 4(4.4)               | 0.871          | 0.351   |
| COPD [n(%)]         | 3(3.3)             | 2(2.2)               | 0.206          | 0.650   |
| Sinus rhythm [n(%)] | 90(100)            | 89(98.9)             | 1.006          | 0.316   |

<sup>§</sup>Plus-minus values are mean±SD. BMI, body mass index; APACHE, acute physiology and chronic health evaluation; HTN, hypertension; CAD, coronary arterial disease; DM, diabetes mellitus; CRF, chronic renal failure; COPD, chronic obstructive pulmonary disease.

**Table 3.** Comparison of optimal images acquisitions between patients with and without mechanical ventilation for evaluation on left and right ventricular functions by echocardiography

| Imaging and parameters               | Study group (n=90)    | Control group (n=90) | $X^2$ value | P value |
|--------------------------------------|-----------------------|----------------------|-------------|---------|
| Eyeballing parameters                |                       |                      |             |         |
| RV function eyeballing [n(%)]        | 78(86.7)              | 85(94.4)             | 3.183       | 0.074   |
| LVEF eyeballing [n(%)]               | 82(88.9)              | 87(97.8)             | 2.421       | 0.119   |
| M-mode parameters                    |                       |                      |             |         |
| TAPSE [n(%)]                         | 65(72.2)              | 82(91.1)             | 10.724      | 0.001   |
| MAPSE [n(%)]                         | 76(84.4)              | 88(97.8)             | 9.878       | 0.002   |
| Pulse doppler parameters             |                       |                      |             |         |
| RVOT VTI [n(%)]                      | 64(71.1)              | 78(86.7)             | 6.538       | 0.011   |
| LVOT VTI [n(%)]                      | 77(85.6)              | 88(97.8)             | 8.800       | 0.003   |
| Endocardium-tracing based parameters |                       |                      |             |         |
| FAC [n(%)]                           | 20(22.2)*             | 58(64.4)             | 32.670      | 0.000   |
| LVEF Simpson [n(%)]                  | 34(37.8) <sup>#</sup> | 73(81.1)             | 35.051      | 0.000   |

RV, Right Ventricle; LVEF, left ventricular ejection fraction; TAPSE, tricuspid annular plane systolic excursion; MAPSE, mitral annular plane systolic excursion; RVOT, right ventricular outflow tract; LVOT, left ventricular outflow tract; VTI, Velocity-Time Integral; FAC, fraction of area change of the right ventricle; LVEF Simpson, LVEF measured with Simpson's rule.

\*Compared to the TAPSE ( $P<0.001$ ) and RVOT VTI ( $P<0.001$ ) in the study group, respectively.

<sup>#</sup>Compared to the MAPSE ( $P<0.001$ ) and LVOT VTI ( $P<0.001$ ) in the study group, respectively.

to obtain optimal images than non-ICU patients. Nevertheless, similar number of eyeballing parameters were obtained in mechanically ventilated patients as in control group. For quantitative parameters acquisition in patients with mechanical ventilation, M-mode based longitudinal function and pulse Doppler-based VTI were much more obtained than endocardium-tracing based parameters.

Transthoracic echocardiography has become an very important method in evaluation of critically ill patients.<sup>[11,12]</sup> Mercado P *et al.*<sup>[13]</sup> found that in critically ill mechanically ventilated patients, transthoracic echocardiography is an accurate and precise method for estimating cardiac output. However, it is more difficult to achieve transthoracic windows in these patients than in non-ICU patients. Pulmonary hyperinflation is one of the limitations for emergent and ICU patients, and positive ventilation obviously can precipitate the situation. Patient positioning is another important factor. Sometimes critically ill patients were unable to cooperate with the exam. In the regular echocardiographic examination, the patient's left arm can be raised towards head to widen the left-side intercostal spaces.<sup>[14,15]</sup> However, this is often hard to accomplish due to an indwelling peripheral vein catheter or arterial catheter in ICU patients. Besides, surgical wounds and drainage tubes often leave the ICU patients without an appropriate checking area. Therefore, high risk surgical patients often have limited image quality. Studies have reported that obese patients tend to have inadequate image quality. There was an overall decrease in the quality of transthoracic echocardiographic images as BMI increases.<sup>[16]</sup> Although the BMI in the two groups were comparable in this study, the ICU patients had higher APACHE scores and were more likely to be accompanied with edema, which might decrease image quality.

We found that for parameters of RV function and LVEF by eyeballing, the ICU patients in study group showed similar acquisition rate of optimal image with the control group, indicating the heart function appraisal from eyeballing method was reliable. Previous study has demonstrated the accuracy of LVEF eyeballing method.<sup>[8,17]</sup> In this study, we incorporated two parameters, RV size and curvature of interventricular septum. RV should appear smaller than the left ventricle and usually be not exceeding two thirds of the size of left ventricle in the standard apical 4-chamber view. Visual assessment of ventricular septal curvature could

help in the diagnosis of RV volume and/or pressure overload. These two parameters were recommended in the guideline for the echocardiographic assessment of right heart in adults.<sup>[4]</sup> Besides its accuracy, the eyeballing method can be easily mastered by clinicians. For example, the ability of physicians to determine LVEF with a broad clinically pertinent category of "normal," "moderately decreased," or "severely decreased" has been repeatedly demonstrated.<sup>[3]</sup> Even medical students could estimate LVEF through eyeballing method with training.<sup>[18]</sup> Besides, eyeballing method is less time-consuming, which is very important for the treatment of ICU patients.

Among the examined parameters, the endocardium-tracing based parameters had the lowest acquisition rate for optimal images. This result was due to the endocardium being hard to be tracked in critically ill patients. LVEF Simpson estimates systolic and diastolic volumes in apical 4-chamber and 2-chamber views that are perpendicular to each other. It is necessary that the endocardium be visible along the entire cavity and for the entire cycle.<sup>[17]</sup> The morphology of the right ventricle is complex. The prominent trabeculations and moderator bands in RV can make identification of endocardial borders challenging.<sup>[19,20]</sup> Positive ventilation-induced lung extension could make the right ventricular endocardium border even harder to track. As the right heart locates anteriorly in the chest and close to the lung, when the probe of echocardiography is placed around the apex, the right heart is easily affected by the extended lungs.

Even though LVEF Simpson and FAC were obtained much less in the study group than the control group, longitudinal functions represented by TAPSE and MAPSE could be good alternatives if needed. TAPSE is one of the most feasible and reproducible parameter that reflects RV systolic function, and it has important prognostic value in critically ill patients.<sup>[4,21,22]</sup> MAPSE was found to be a highly accurate predictor for LVEF, even by an untrained observer.<sup>[23]</sup> We also found that VTI was much easier to acquire than LVEF. There has been study pointing out that Doppler measurements are very reproducible.<sup>[24]</sup> VTI assessed by pulsed Doppler is more useful than LVEF for the management of critically ill patients. Stroke volume measurements which calculated by VTI before and after fluid administration or inotrope infusion allow the effect of treatment to be quantified.<sup>[25]</sup>

This study has several limitations. First, most of

the patients admitted to our ICU were surgical patients, the proportion of patients with dressing and drainage tubes was high, which might be different from ICU in other institutes. Second, the sample size was relatively small. Third, we only investigated the fundamental parameters of echocardiography, did not include segmental wall motion assessment, valve assessment, and advanced measurements such as speckle tracking and three-dimensional echocardiography. Finally, the results were all based on bedside echocardiographic examination *via* portable echocardiography, which might impair the image quality. Nevertheless, most bedside echocardiographic examinations in clinical practice are implemented through portable machine, therefore, we think the results in this study are reliable in reflecting image acquisition of echocardiography in ICU setting.

To conclude, the TTE images tend to be obtained with impaired quality in mechanically ventilated patients. For measurements of the quantitative parameters, M-mode based longitudinal function and pulse Doppler-based VTI were less likely to be affected than endocardium-tracing based parameters. Eyeballing could be an alternative method of echocardiography for mechanically ventilated patients.

### Conflict of interests

*All authors disclosed no conflicting interests.*

## REFERENCES

1. Narasimhan M, Koenig SJ, Mayo PH. Advanced echocardiography for the critical care physician: part 2. *Chest* 2014; 145(1):135-42. doi: 10.1378/chest.12-2442.
2. Moore CL, Rose GA, Tayal VS, et al. Determination of left ventricular function by emergency physician echocardiography of hypotensive patients. *Acad Emerg Med* 2002; 9(3):186-93. doi: 10.1197/aemj.9.3.186.
3. Randazzo MR, Snoey ER, Levitt MA, et al. Accuracy of emergency physician assessment of left ventricular ejection fraction and central venous pressure using echocardiography. *Acad Emerg Med* 2003; 10(9):973-7. doi: 10.1111/j.1553-2712.2003.tb00654.x
4. Rudski LG, Lai WW, Afilalo J, et al. Guidelines for the echocardiographic assessment of the right heart in adults: A report from the American Society of Echocardiography. *J Am Soc Echocardiogr* 2010; 23(7):685-713. doi: 10.1016/j.echo.2010.05.010.
5. Jensen MB, Sloth E, Larsen KM, et al. Transthoracic echocardiography for cardiopulmonary monitoring in intensive care. *Eur J Anaesth* 2004; 21(9):700-7. doi: 10.1097/00003643-200409000-00006.
6. Popescu BA, Andrade MJ, Badano LP, et al. European Association of Echocardiography recommendations for training, competence, and quality improvement in echocardiography. *Eur J Echocardiogr* 2009; 10(8):893-905. doi: 10.1093/ejechocard/jep151.
7. American College of Emergency Physicians. Emergency ultrasound guidelines. *Ann Emerg Med* 2009; 53(4):550-70.
8. Gudmundsson P, Rydberg E, Winter R, et al. Visually estimated left ventricular ejection fraction by echocardiography is closely correlated with formal quantitative methods. *Int J Cardiol* 2005; 101(2):209-12. doi: 10.1016/j.ijcard.2004.03.027.
9. Quinones MA, Otto CM, Stoddard M, et al. Recommendations for quantification of Doppler echocardiography: A report from the Doppler quantification task force of the nomenclature and standards committee of the American Society of Echocardiography. *J Am Soc Echocardiogr* 2002; 15(2):167-84. doi: 10.1067/mje.2002.120202.
10. Lang RM, Badano LP, Mor-Avi V, et al. Recommendations for cardiac chamber quantification by echocardiography in adults: An update from the American Society of Echocardiography and the European Association of Cardiovascular Imaging. *J Am Soc Echocardiogr* 2015; 28(1):1-39. doi: 10.1016/j.echo.2014.10.
11. Feng M, McSparron JJ, Kien DT, et al. Transthoracic echocardiography and mortality in sepsis: analysis of the MIMIC-III database. *Intensive Care Med* 2018; 44(6):884-92. doi: 10.1007/s00134-018-5208-7.
12. Moreno O, Ochagavia A, Artigas A, et al. Evaluation of intensivist basic training in transthoracic echocardiography in the postoperative period of heart surgery. *Med Intensiva* 2019; 43(9):538-45. doi: 10.1016/j.medin.2018.06.004.
13. Mercado P, Maizel J, Beyls C, et al. Transthoracic echocardiography: an accurate and precise method for estimating cardiac output in the critically ill patient. *Crit Care* 2017; 21(1):136. doi: 10.1186/s13054-017-1737-7.
14. American College of Emergency Physicians. Emergency ultrasound imaging criteria compendium. American College of Emergency Physicians. *Ann Emerg Med* 2006; 48(4):487-510. doi: 10.1016/j.annemergmed.2006.07.946.

15. Sarti A, Cipani S, Innocenti C. Ultrasound morphology of the heart: transthoracic examination. In: Sarti A, Lorini F. editors. Textbook of echocardiography for intensivists and emergency physicians. Milan: Springer; 2019. p.21-36.
16. Siadecki SD, Frasure SE, Lewiss RE, et al. High body mass index is strongly correlated with decreased image quality in focused bedside echocardiography. *J Emerg Med* 2016; 50(2):295-301. doi: 10.1016/j.jemermed.2015.07.023.
17. Sarti A, Lorini FL. Echocardiography for intensivists. Milan: Springer; 2012. p.81-2.
18. Hope MD, de la Pena E, Yang PC, et al. A visual approach for the accurate determination of echocardiographic left ventricular ejection fraction by medical students. *J Am Soc Echocardiogr* 2003; 16(8):824-31. doi: 10.1067/S0894-7317(03)00400-0.
19. Horton KD, Meece RW, Hill JC. Assessment of the Right Ventricle by Echocardiography: A Primer for Cardiac Sonographers. *J Am Soc Echocardiogr* 2009; 22(7):776-92. doi: 10.1016/j.echo.2009.04.027.
20. Chan KL, Veinot JP. Right ventricular diseases. In: Chan KL. Anatomic basis of echocardiographic diagnosis. London: Springer; 2010. p.207-26.
21. Kaul S, Tei C, Hopkins JM, et al. Assessment of right ventricular function using two-dimensional echocardiography. *Am Heart J* 1984; 107:526-31. doi: 10.1016/0002-8703(84)90095-4.
22. Gajanana D, Seetha Rammohan H, Alli O, et al. Tricuspid annular plane systolic excursion and its association with mortality in critically ill patients. *Echocardiography* 2015; 32(8):1222-7. doi: 10.1111/echo.12926.
23. Matos J, Kronzon I, Panagopoulos G, et al. Mitral annular plane systolic excursion as a surrogate for left ventricular ejection fraction. *J Am Soc Echocardiogr* 2012; 25(9):969-74. doi: 10.1016/j.echo.2012.06.011.
24. Robson SC, Murray A, Peart I, et al. Reproducibility of cardiac-output measurement by cross-sectional and doppler echocardiography. *Brit Heart J* 1988; 59(6):680-4. doi: 10.1136/hrt.59.6.680.
25. Huang SJ. Measuring cardiac output at the bedside. *Curr Opin Crit Care* 2019; 25(3):266-72. doi: 10.1097/MCC.0000000000000599.