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Eckhard Mauermann MD, MSc. , Michael Vandenheuvel MD. ,
Katrien François MD, PhD. , Stefaan Bouchez MD. ,
Patrick Wouters MD, PhD.

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A Novel Speckle-Tracking Based Method for Quantifying Tricuspid Annular Velocities in TEE

Eckhard Mauermann, Michael Vandenheuvel,

Katrien François, Stefaan Bouchez, Patrick Wouters

Eckhard Mauermann, MD, MSc. 1) Department for Anesthesiology and Perioperative Medicine, C. Heymanslaan 10, 9000, Ghent University Hospital, Ghent, Belgium AND 2) Department for Anesthesiology, Surgical Intensive Care, Prehospital Emergency Medicine, and Pain Therapy, Basel University Hospital, Spitalstrasse 21, 4031 Basel, Switzerland. Corresponding Author. Eckhard.Mauermann@usb.ch

Michael Vandenheuvel, MD. Department for Anesthesiology and Perioperative Medicine, C. Heymanslaan 10, 9000, Ghent University Hospital, Ghent, Belgium.

Katrien François, MD, PhD. Department of Cardiac Surgery, Ghent University Hospital, C. Heymanslaan 10, 9000, Ghent, Belgium.

Stefaan Bouchez, MD. Department for Anesthesiology and Perioperative Medicine, C. Heymanslaan 10, 9000, Ghent University Hospital, Ghent, Belgium.

Patrick Wouters, MD, PhD. Department for Anesthesiology and Perioperative Medicine, C. Heymanslaan 10, 9000, Ghent University Hospital, Ghent, Belgium.

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Abstract

Objectives: We present a novel speckle-tracking-based option for measuring tricuspid annular velocities in the midesophageal 4-chamber view (ME4C), which we compared to velocities measured by tissue Doppler in the apical-4 chamber view (AP4C). As this method was based on a modified speckle-tracking-based measurement of TAPSE, we also compared TAPSE by speckle-tracking in the ME4C to TAPSE by M-mode in the AP4C.

We hypothesized that velocities measured by speckle-tracking in TEE would be similar, correlate and agree with those measured by tissue Doppler in TTE.

Design: prospective diagnostic study with randomization of the order of postinuduction echocardiography views by TTE (AP4C) and TEE (ME4C). Images were both acquired and analyzed by two echocardiographers independently. The primary outcome was S'; secondary outcomes were E', A', and TAPSE.

Setting: single university hospital.

Participants: consecutive adult patients undergoing cardiac surgery (mainly CABG).

Interventions: none.

Main Results: Complete data was available in 24/25 patients. For the primary outcome, S' measured by speckle-tracking in the ME4C correlated and agreed with S' measured by tissue Doppler in the AP4C (S'_{STE}=0.87S_{TDI}+0.60, P<0.001, r=0.78; mean bias -0.6cm/s, 95%LoA -3.5 to 2.4cm/s). Similarly results were found for E', but not A' (E'_{STE}=0.69E'_{TDI}+2.37, P<0.001, r=0.71; mean bias 0.1cm/s, 95%LoA -2.5 to 2.8cm/s; A'_{STE}=0.15A'_{TDI}+11.17, P=0.629). TAPSE measurements by our modified speckle-tracking-based technique were similar to TAPSE be M-mode (18.2±5.5mm and 17.1±3.9mm, respectively).

Conclusions: Tricuspid annular velocities (S'$_{STE}$, E'$_{STE}$) determined by speckle-tracking in TEE seem promising surrogates for velocities measured in TTE. This may be important for perioperative assessment of the right ventricle.

Key Words: tricuspid annular velocity; longitudinal right ventricular function; speckle-tracking; tricuspid annular plane systolic excursion (TAPSE).

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Introduction

Assessing right ventricular performance – which has been shown to be a predictor of mortality in a number of perioperative settings[1-3] – is as important[4-9] as it is difficult in transesophageal echocardiography (TEE).[10, 11] However, current guidelines regarding the right ventricle,[8] quantification of myocardial chamber and function,[12] and diastolic function[13] are based on transthoracic echocardiography (TTE). On account of the longitudinal muscle fibre orientation and resultant contractility,[14, 15] tricuspid annular plane systolic excursion by M-mode (TAPSE$_{M\text{-}MODE}$) or tricuspid annular velocities by tissue Doppler imaging (TDI) are recommended surrogates for global right ventricular function.[8] Furthermore, a number of studies have shown tricuspid annular velocities and displacement to correlate with global right ventricular function[8, 9, 16-20] and clinical outcomes. [8, 9, 17, 21] However, both M-mode and TDI are highly angle-dependent technologies and there is inherent misalignment of the ultrasound beam in TEE. It would be desirable to find similar measures of tricuspid annular velocity in TEE.

Recently, a measurement method of TAPSE based on speckle-tracking technology ($TAPSE_{STE}$) has emerged as a validated method of measuring displacement in TEE.[22, 23] Specifically, the studies showed that $TAPSE_{STE}$ measured in the midesophageal 4-chamber view (ME4C) reliably correlated and agreed with $TAPSE_{M\text{-}MODE}$ measured in the apical 4-chamber view (AP4C). Briefly, this technology analyses 2D-cineloops by tracking the position of the lateral tricuspid annulus relative to the apex and then measuring the distance between these points for each frame over a given R to R interval.[8, 12]

We wondered whether or not differentiating the displacement-time relationship generated by a commercially available software could yield clinically useful measures of tricuspid annular velocities. Systolic velocities (S') are less influenced by loading conditions, [8, 24] which may be very important in the dynamic perioperative period (i.e. the influence of positive pressure ventilation, anaesthesia, blood loss, extra corporeal circulation, etc.),[25, 26] Additionally, diastolic annular velocities also yield important information and are used in the classification of diastolic function.[13]

Specifically, the main objective of this study was to ascertain whether or not accurate, precise, and reliable measurements of S', E' and A' could be obtained by measuring displacement over time via a modified, noise-reduced, speckle-tracking based method (i.e. $TAPSE_{STE}$) and then differentiating with respect to time (i.e. S'_{STE}, E'_{STE}, A'_{STE}). For this purpose, we first validated our modified method of measuring $TAPSE_{STE}$ in the ME4C and then compared the differentiation over time of this method (i.e. S'_{STE}, E'_{STE}, and A'_{STE}) to velocities measured in the AP4C by tissue Doppler imaging (i.e. S'_{TDI}, E'_{TDI}, and A'_{TDI}).

Methods

Study Design, Participants, and End-Points

This is an explorative analysis of a diagnostic study based on a high-quality dataset of randomized and standardized echo views in consecutive adult patients undergoing cardiac surgery from February 2017 to July 2017 at a university hospital. Patients with irregular heart rhythms, severe annular calcification, or tricuspid/mitral valve surgeries were not eligible. All patients provided written informed consent for their participation. This study was approved of by an institutional review board and registered prior to patient enrolment at clinicaltrials.gov (NCT03088943, Date of registration: February 14, 2017).

The primary endpoint was systolic tricuspid annular plane velocity by speckle-tracking (S'_{STE}) in the ME4C, which we compared to our reference standard, S' by TDI (S'_{TDI}) in the AP4C. Secondary outcomes were E'_{STE} and A'_{STE} in the ME4C, which we analogously compared to E'_{TDI} and A'_{TDI} in the AP4C. As a proof of concept, we also compared S'_{STE}, E'_{STE}, and A'_{STE} to S'_{TDI}, E'_{TDI}, and A'_{TDI} all in the AP4C. In order to validate the modified measurement method of TAPSE by speckle-tracking ($TAPSE_{STE}$) from which velocities were calculated, we first compared $TAPSE_{STE}$ in the ME4C to $TAPSE_{M\text{-}MODE}$ in the AP4C. In order to justify our altered approach, we also compared speckle-tracking-derived velocities using the right ventricular apex as a reference point.

Echocardiography Image Acquisition and Analysis

During a period of hemodynamic stability and following induction with 2mg kg^{-1} propofol, 2-3 µg kg^{-1} fentanyl, 0.5 mg kg^{-1} rocuronium, and sevoflurane maintenance, two echocardiographers acquired TTE and TEE images independently in a balanced randomized order (Figure 1). Randomization was performed by an otherwise uninvolved study nurse by a sealed envelope method and envelopes were opened in the operating room upon patient arrival. Images were then analysed with each echocardiographer examining the images they themselves had acquired. One echocardiographer repeated analyses after 4 weeks. All images were acquired in the supine position in end-exspiratory apnoea using a Philips iE33 ultrasound machine, a S5-1 (TTE) transducer, and a X7-2t (TEE) transducer (all Philips, Amsterdam, Netherlands). S'_{TDI}, E'_{TDI}, A'_{TDI}, and $TAPSE_{M\text{-}MODE}$ in the AP4C was measured as the mean value of three consecutive beats.

S'_{STE}, E'_{STE}, and A'_{STE} were calculated by transforming the displacement-time curve of $TAPSE_{STE}$ measurements made using an offline workstation with QLAB 10.5 (Philips Healthcare, Andover, MA, USA; Figure 2A and B, top). Briefly, this software asks the user to place three points: two at the tricuspid annulus (blue and orange in Figure 2A and 2B, top) and one at the apex of the right ventricle (red in Figure 2A, top). The software then measures the difference from both the lateral tricuspid annulus (blue) and the medial annulus (orange) to the apex (red) at each frame over an R-to-R interval (one frame is one dot on the resultant displacement-time curves). For our analysis, we examined the lateral tricuspid annulus only (blue curve). Our preliminary analyses suggested that using the apex as the point of reference as foreseen by the vendor (Figure 2, Panel A, top) and as previously published,[22, 23] led to substantial noise not relevant to $TAPSE_{STE}$, but of substantial relevance for velocities (Figure 2A, bottom). Increased noise has been shown to decrease the number of traceable speckles compared to TTE,[27] and random noise will increase peak velocities. As a consequence, we opted to focus exclusively on movement of the tricuspid annulus relative to a fixed reference point, much like TDI, which calculates velocities from frequencies emitted and received by an immobile transducer. Specifically, we used a reference point at an equidistant, mirror-image point at end-diastole (red circle in Figure 2B, top), which led to less noisy velocities (Figure 2B, bottom). While other reference points may also have been used (ideally any collinear point to the plane of motion of the tricuspid annulus), the mirror image point has the benefit of being relatively easy to eyeball and far enough from the tricuspid annulus to reduce residual misalignment. An alternative reference point was required for two reasons: first, it is not possible to "turn off" tracking at reference points and using a region of interest off of the actual 2D loop ensures immobility, and, second, selecting a point beyond the apex (i.e. in the bottom right of the image) frequently led to movement due to tracking of the ECG. Supplemental Videos 1A and 1B show the loops of the images in Figure 2. In addition to visually ensuring adequate tracking, we also examined the shape of the resultant displacement-time curve (analogous to the shape of the $TAPSE_{M-MODE}$ curve). Nonetheless, we also examined speckle-tracking based velocities using the apical reference point.

In a second step (Figure 2A and B, bottom), we then exported the displacement-time data from QLAB into R 3.4.3 (The R Foundation for Statistical Computing, Vienna, Austria). Each point was plotted (black points), a spline was placed on the data without any smoothing (red line), and the first derivative was plotted (blue line). Values for the tricuspid annular velocities and displacement were generated automatically in R and visually confirmed (analogous to assessing the shape of a TDI curve).

Statistical Analysis

Summary statistics for all endpoints are based on the mean patient measurement (e.g. n=25) of both assessor's first measurement, unless stated otherwise. For full transparency, figures also show each measurement pair (i.e. 3 measurements per patient; from both assessors and the repeat measurements of one assessor).

As the basis of our velocity measurements, we first validated our modified method for measuring $TAPSE_{STE}$ by plotting $TAPSE_{STE}$ in the ME4C against $TAPSE_{M-MODE}$ in the AP4C. We reported slope and Pearson's r as a parameter of model fit and examined agreement by a Bland-Altman plot.

For the study's primary (S'_{STE} in the ME4C vs. S'_{TDI} in the AP4C) and secondary velocity endpoints (E'_{STE} vs. E'_{TDI}; A'_{STE} vs. A'_{TDI}) we assessed possible differences by paired Student's t-tests, by correlation, and by Bland-Altman plots as above. Similar analyses were performed using the apical reference point (as a justification of our alternative method) and using speckle-tracking based velocities in the AP4C (as a proof of methodology).

We assessed both interrater and intrarater reliability by interclass correlation coefficients (ICCs). Specifically, we used a two-way random-effect model, mean of k-raters, and absolute agreement for interrater reliability (ICC(2,k)), and two-way mixed effects, mean of k measurements, and absolute agreement (ICC(3,1)) for intrarater reliability as defined by Shrout and Fleiss.[28] Interobserver reliability involved independent image acquisition and analysis, while intraobserver reliability involved a re-analysis of images already acquired by that assessor 4 weeks after initial measurements. We classified ICCs as poor (<0.40), fair (0.41-0.59), good (0.60 – 0.74), and excellent (>0.74).[29]

As an explorative analysis, the sample size determined by the size of the data set (clinicaltrials.gov NCT03088943). All analyses were conducted in R 3.4.3.

Results

Analysis of Echocardiographic Parameters

Figure 1 shows a flow diagram of patient inclusion for eligible patients. A total of 6 patients were not eligible due to atrial fibrillation, while none were ineligible due to severe annular calcification. Of the 32 eligible patients, 7 were excluded due to postponing of surgery, declining to participate, or language barriers. Data was largely complete with S'_{STE}, E'_{STE}, and A'_{STE} in the ME4C available in all 25 patients and S'_{TDI}, E'_{TDI}, and A'_{TDI} in the AP4C available in 24/25 patients (one excluded for urgency). All patients were analysed as allocated.

Figure 3 shows the modified $TAPSE_{STE}$ in the ME4C and the $TAPSE_{M\text{-}MODE}$ in the AP4C with mean values of 18.2±5.5mm and 17.1±3.9mm, respectively. Correlation was significant ($TAPSE_{STE}=0.79TAPSE_{M\text{-}MODE} + 4.96$; $P<0.001$) with fair model fit ($r=0.56$) and agreement showed a mean bias of 1.4mm (95%LoA = -7.8 to 10.5mm).

Figure 4 shows S'_{STE}, E'_{STE}, and A'_{STE} in the ME4C compared to S'_{TDI}, E'_{TDI}, and A'_{TDI} in the AP4C. In terms of correlation, S'_{STE} in the ME4C correlated with S'_{TDI} in the AP4C with excellent model fit ($S'_{STE}=0.87S_{TDI}+0.60$, $P<0.001$, $r=0.78$). Similarly, E'_{STE} in the ME4C correlated with E'_{TDI} in the AP4C with good model fit ($E'_{STE}=0.69E'_{TDI}+2.37$, $P<0.001$, $r=0.71$). A'_{STE} did not correlate ($A'_{STE}=0.15A'_{TDI}+11.17$, $P=0.629$, $r=0.11$). In terms of agreement, S'_{STE} and E'_{STE} showed mean biases of -0.6cm/s (95%LoA -3.5 to 2.4cm/s) and 0.1cm/s (95%LoA -2.5 to 2.8cm/s). Mean bias for A'_{STE} was 2.4cm/s (95%LoA -7.3 to 12.1cm/s). Using the "noisy" apex as a reference point showed a lack of correlation and a more than doubling of the 95% limits of agreement (Supplemental Figure 1).

Figure 5 shows velocities in the AP4C only, measured by both speckle-tracking as well as by TDI. All three velocities correlated with one another with good to excellent model fit

(S'_{STE}=0.91S'_{TDI}+0.60, P<0.001; r=0.79; E'_{STE}=0.91E'_{TDI}+0.84, P<0.001, r=0.69; A'_{STE}=0.66S_{TDI}+3.63, P<0.001, r=0.73). Agreement was unbiased.

Reproducibility of Speckle-Tracking-Based Measurements

Table 1 shows intraobserver and interobserver reliability. Intraobserver reliability involved image analysis, while interobserver reliability involved both image acquisition and analysis. $S'_{TDI,}$ $E'_{TDI,}$ and A'_{TDI} all showed excellent intrarater reliability and interrater reliability. S'_{STE} showed good to excellent reliability and E'_{STE} showed fair to good reliability. While A'_{STE} showed poor interobserver reliability and excellent interobserver reliability in the ME4C, these were good and fair in the AP4C.

Discussion

In this study, we compared novel speckle-tracking-based tricuspid annular velocities measured in TEE to gold standard TDI-based velocities in TTE. This early analysis suggests that this is an accurate and reliable method for assessing S'_{STE} and E'_{STE}, but not A'_{STE}.

Modification of $TAPSE_{STE}$ measurements

Two recent publications have examined displacement of the tricuspid annulus by speckle-tracking. Both used the same software as in this study, but, unlike our study, used the apex as the reference point. As we performed a modification of this technique and as $TAPSE_{STE}$ is the basis of our velocity measurements, a brief summary is justified.

Markin et al.[22] examined post-induction $TAPSE_{M\text{-}MODE}$ in the AP4C and $TAPSE_{STE}$ in the ME4C in 112 patients. Images were acquired for 100 patients in a non-randomized manner by a single expert echocardiographer. $TAPSE_{STE}$ in the ME4C to show slightly longer (+1.5mm) mean measurements than $TAPSE_{M\text{-}MODE}$ in the AP4C with good model fit (Pearson's r=0.62). Agreement was not assessed. Interrater reproducibility of $TAPSE_{STE}$ in the ME4C showed a Pearson's correlation coefficient of 0.80, although only 84 images could be assessed by the inexperienced reviewer.

Shen et al. [23] compared post-induction $TAPSE_{STE}$ in the ME4C to awake, pre-induction $TAPSE_{M\text{-}MODE}$ in the AP4C of exams taken in the 3 months prior to surgery in 60 patients. Despite the important limitation imposed by the timing of measurements, they also found significant correlation between $TAPSE_{STE}$ in the ME4C and $TAPSE_{M\text{-}MODE}$ in the AP4C (slope=0.82, r=0.87) and good agreement in Bland-Altman plots (mean bias 2.4mm; 95% limits of agreement 2.6mm).

Our modified $TAPSE_{STE}$ measurements showed similar results as in the two previous studies. Our mean difference of $TAPSE_{STE}$ in the ME4C to the $TAPSE_{M\text{-}MODE}$ in the AP4C was

1.4mm, nominally lower than those of the other two studies (1.5mm and 2.4mm). This may be due to decreased noise by immobilizing the reference point. We also showed a similar degree of correlation (slopes: 1.07, 0.82, and 0.79). Model fit was also similar to the Markin study (r=0.62 vs. 0.56). Variability in our study was greater than in the Shen study, which we attribute to two echocardiographers acquiring and analysing their own images in ventilated patients rather than one echocardiographer acquiring optimized images in the left later decubitus position of spontaneously breathing, cooperative patients.

Speckle-Tracking-Based Velocities: Relevance of Findings

The correlation of S'_{STE} in TEE with S'_{TDI} in the TTE is encouraging. The potential clinical relevance of these results – which could easily be made available on an echo machine for immediate analysis – are four-fold.

First, this method allows for quantification of right ventricular annular velocities in TEE, which would otherwise be unavailable or inaccurate. The use of TDI in the ME4C as well as other TEE views has repeatedly shown systematic underestimation of velocities.[30-32] Furthermore, in the early postoperative phase, TEE images can almost always be attained and speckle-tracking velocities can be calculated, while an AP4C may be difficult to obtain in ventilated patients and/or after thoracic surgery. Second, unlike $TAPSE_{STE}$, which is more dependent on loading conditions,[8, 12] this method also allows for the assessment of diastolic function and filling pressures of the right ventricle by E'_{STE}. Although not relevant in all patients, this may be a major benefit in select populations. Third, the need to only visualize the tricuspid annulus' motion relative to a post-processing fix point may enable assessment in a number of situations in which the right ventricular free wall may only be partially or poorly visible (e.g. after previous surgery, post pump, aortic calcification, etc.). Additionally, as underscored by a complete lack of correlation using the apex as a reference point, the image may focus entirely on the lateral tricuspid annulus. Fourth, speckle-tracking-based measurement of tricuspid annular velocities can be determined from virtually any pre-existing 2D-cine loop of the ME4C (or the AP4C for that matter). As these are arguably the single most common acquired images in any TEE (or TTE) exam, this suggests that one could examine earlier images of patients going on to develop right ventricular problems. It may also create a number of opportunities for large (retrospective) studies.

Challenges and Image Optimization

While S' and E' are clearly the more relevant tricuspid annular velocities, the lacking correlation of A'_{STE} in the ME4C merits attention.

We attribute this three main factors. First, the commercial software used for measuring the displacement-time relationship uses a beat-by-beat analysis based on the R-to-R interval. Consequently, parts of the A-wave were sometimes prematurely truncated or attributed to the next beat, which adds variability. Secondly, as evident from the timing in the displacement curve in Figure 2, systole is almost twice as long and has almost twice as many frames (points) as early relaxation or three times as long as the atrial kick, yielding a more robust analysis. Particularly with a relatively low number of frames, a quickly and laterally moving tricuspid annulus in a 2D image may be more difficult to track in the ME4C than AP4C. Furthermore, the speckle-tracking and possibly smoothing algorithms are not publicly known, are based on the AP4C of the left ventricle, and are known to show considerable intervendor variability.[33] Taken together, a truncated A' wave, moving rapidly in only a few frames in the unfavorable lateral direction of 2D echo images and analyzed by an unknown tracking/smoothing algorithms designed for the left ventricle in TTE may explain this difference. The improved correlation and agreement of speckle-tracking based velocities in the AP4C along ultrasound beams (e.g. a longitudinal motion) with TDI measurements in the AP4C underscores this point.

As speckle-tracking analyses are based on 2D cine-loops, an optimization of these images is important. Although commonly cited as an angle-independent technology, a modest degree of angle-dependence may exist for speckle-tracking on the basis of the characteristics of the underlying 2D cine-loop.[34, 35] Spatiotemporal resolution should be optimized by decreasing image depth and, particularly, sector width. Wider sectors lead to less robust tracking,[36] which affects lateral motion more than axial motion. As our method shows that only the tricuspid annulus needs to be visualized, frame rate may be greatly increased by narrowing the sector and decreasing depth. Secondly, optimizing the focus increases the density of ultrasound beams and thereby the resolution of particularly lateral tracking.[34] Third, the frequency of ultrasound probes in TEE is higher than in TTE, which increases near-field resolution at the cost of far field resolution. Fourth, acoustic shadowing (particularly from valvular structures) may decrease tracking quality, although at the annulus rather than free wall this may be less of an issue. It is worth emphasizing that our images and analyses were not optimized to focus on the tricuspid annulus, but rather to show the right ventricle and particularly the free wall in its entirety. A priori optimization may further increase the quality of speckle-tracking-based velocities and reduce the discrepancy we observe in A'_{STE}.

Strengths and Limitations of the Study

This study has some important strengths in addition to its novel aspect and the potential resultant clinical relevance. First, we made speckle-tracking and conventional measurements in a randomized order of ME4C and AP4C views and under identical conditions. Secondly, both image acquisition and analyses were made by two independent assessors. Although this may increase variability compared to other studies, it mirrors clinical work: when asking another echocardiographer for their opinion (e.g. for potential paravalvular leakage) it is unlikely that this person will only examine previously acquired images. Third, in terms of design, we first validated the modified speckle-tracking-based displacement measures

($TAPSE_{STE}$) comparing our results with other studies and then compared our novel derived velocities with the clinical TTE gold standard. Fourth, we also demonstrated that using a noisy apex in the far field as a reference point is not beneficial and its visualization superfluous.

However, this study also has some limitations. First, it is an explorative secondary analysis of a small, but well-designed study, and the results require confirmation. The original study was designed to examine conventional and speckle-tracking based measures of the right ventricular free wall and was not optimized for the tricuspid annulus. Nonetheless, this highlights that velocities can be obtained from virtually any previously acquired 2D-cine loop. Second, we included patients undergoing mainly CABG surgery. Although sufficient for answering the research question posed, it would be interesting to confirm these results in larger and other populations (e.g. severely reduced EF, right ventricular hypertrophy, children, etc.). Third, our transformation of a modified $TAPSE_{STE}$ to S'_{STE}, E'_{STE}, and A'_{STE} was self-made. However, our primary aim was to test accuracy and precision, and our results underscore the need for a commercial solution, which could easily and quickly be made available on an echocardiography machine. True to this aim, we did not perform any type of smoothing, averaging, or other modification of velocities. Fourth, our reference point is somewhat arbitrary and other reference points may potentially also be used. Ideally, velocities could be measured frame to frame (much like velocity vectors available in some software), but for a comparison to TDI, which also uses a single fix point (the transducer), our approach seems justified. Fifth, the increased measures of variation observed in this study and previous studies[22] for speckle-tracking-based velocities and displacement (e.g. the 95% limits of agreement and ICCs) should be further examined. Given that the apex need not be visualized, zooming in on the tricuspid annulus only to improve resolution and frame rates, may be promising. Finally, our novel approach is based on the hardware, software, algorithms, etc. used and may vary when using other material and vendors.

In summary, tricuspid annular velocities (S'_{STE}, E'_{STE}) determined by speckle-tracking in TEE seem promising surrogates for velocities measured in TTE. Exploring both possible options for increasing precision of this unbiased, speckle-tracking-based method, as well as the correlation with clinical outcomes and patient management remain to be performed. Nonetheless, even at present, this novel technology enables unbiased assessment of systolic and diastolic velocities from any previously acquired 2D loops.

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Figure and Video Legends:

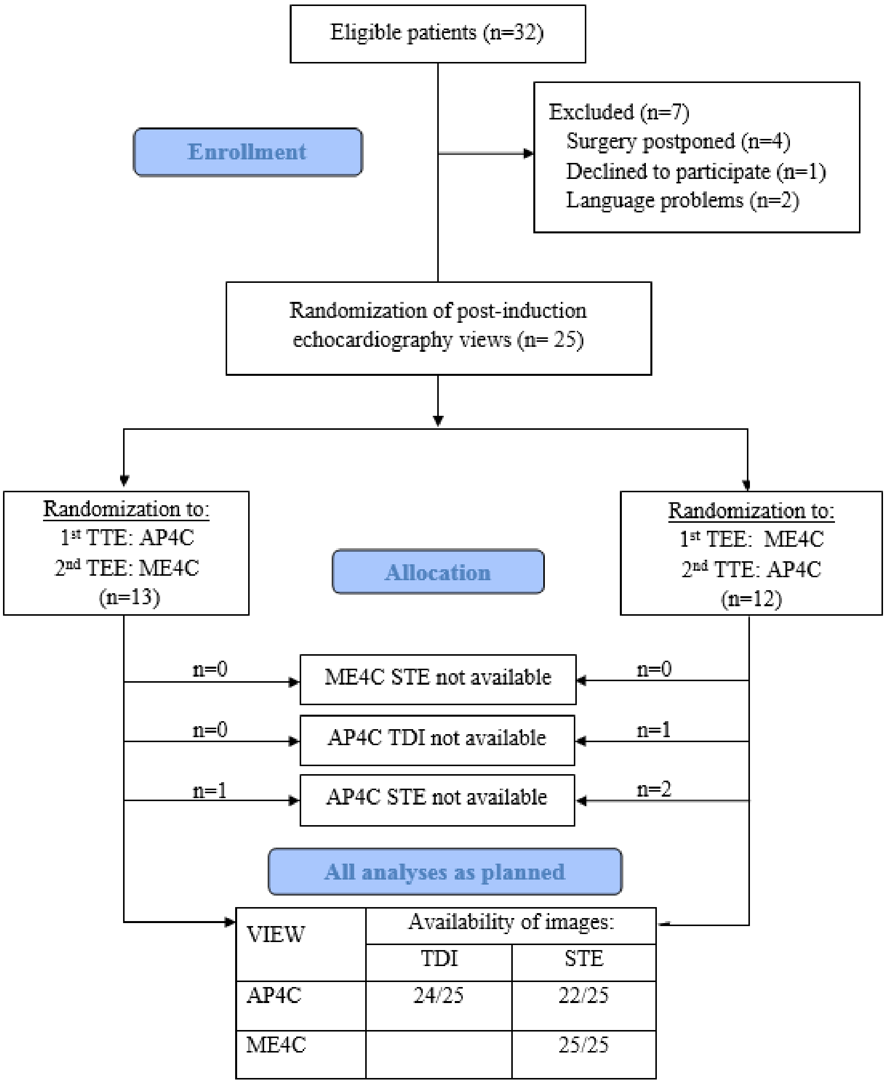

Figure 1: Flow Chart of Patient Inclusion and Available Data

AP4C = apical 4-chamber view, ME4C = mid-esophageal 4-chamber view, STE = speckle-tracking echocardiography, TDI = tissue Doppler imaging, TEE = transesophageal echocardiography, TTE = transthoracic echocardiography.

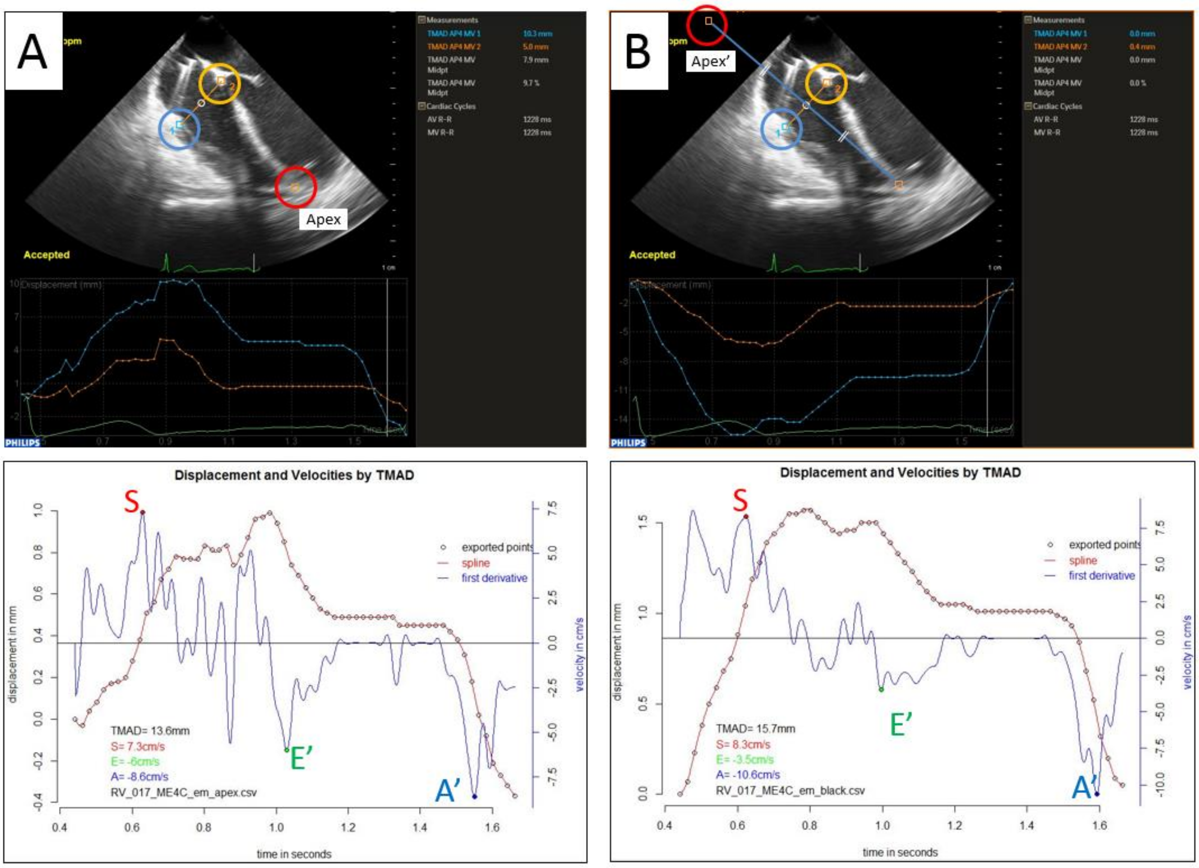

Figure 2: Derivation of S_{STE} in a Two-Step Approach

Top panels illustrate the measurement of tricuspid annular plane displacement using commercial software; bottom panels show measurement of velocities and peak velocity determination using a custom-made code in R. The left side (A) shows the vendor-endorsed method using the apex as a point of reference, while (B) shows our modified method. Note the decrease in noise in displacement and velocities in B. Supplemental Videos are available for both A and B.

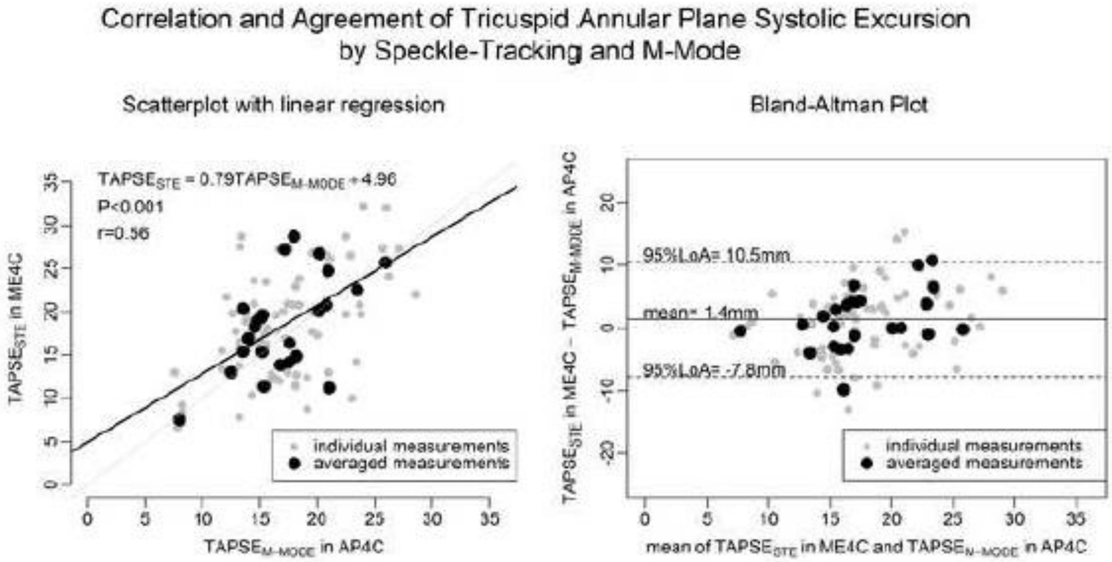

Figure 3: Validation of the Modified Method of Determining $TAPSE_{STE}$

AP4C = apical 4-chamber view, ME4C = mid-esophageal 4-chamber view, $TAPSE_{M\text{-}MODE}$ = tricuspid annular plane systolic excursion by M-mode, $TAPSE_{STE}$ = tricuspid annular plane systolic excursion by speckle tracking. The dotted line shows a line of perfect 1:1 correlation, while the solid line shows the regression line from the data.

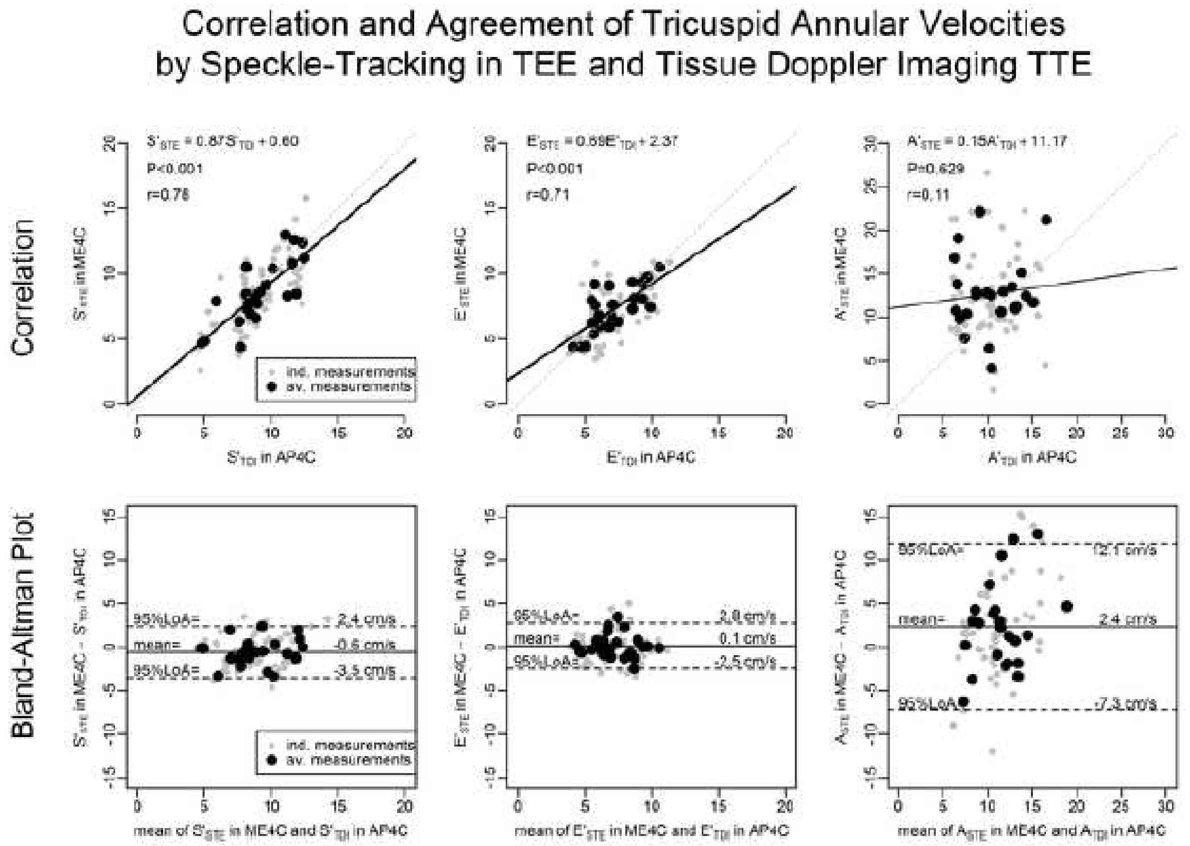

Figure 4: Correlation and Agreement of Tricuspid Annular Velocities Based on Speckle-Tracking and Tissue Doppler

A'_{STE} = tricuspid annular velocity (diastolic, atrial) measured by speckle-tracking echocardiography, A'_{TDI} = tricuspid annular velocity (diastolic, atrial) measured by tissue Doppler imaging, AP4C = apical 4-chamber view, E'_{STE} = tricuspid annular velocity (diastolic, early) measured by speckle-tracking echocardiography, E'_{TDI} = tricuspid annular velocity (diastolic, early) measured by tissue Doppler imaging, ME4C = mid-esophageal 4-chamber view, S'_{STE} = tricuspid annular velocity (systolic) measured by speckle-tracking echocardiography, S'_{TDI} = tricuspid annular velocity (systolic) measured by tissue Doppler imaging. The dotted line shows a line of perfect 1:1 correlation, while the solid line shows the regression line from the data.

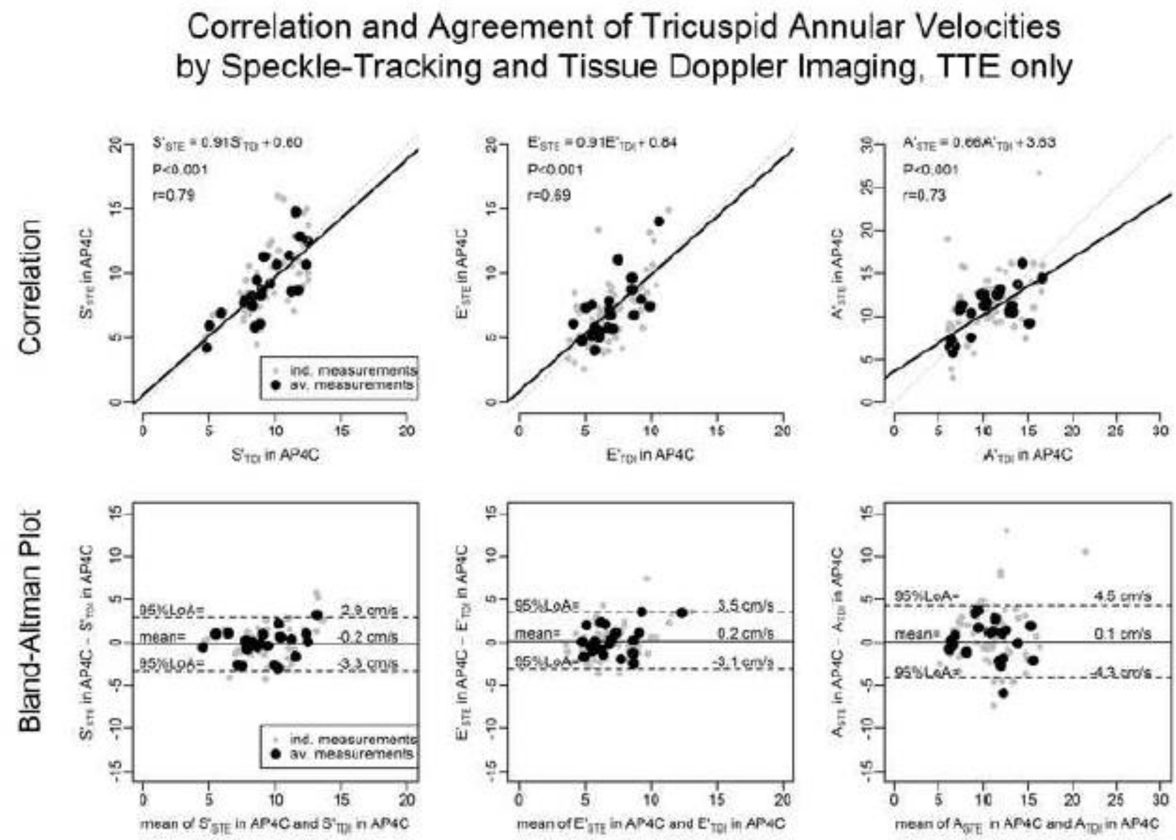

Figure 5: Correlation and Agreement of Tricuspid Annular Velocities Based on Speckle-Tracking and Tissue Doppler, TTE Only

A'$_{STE}$ = tricuspid annular velocity (diastolic, atrial) measured by speckle-tracking echocardiography, A'$_{TDI}$ = tricuspid annular velocity (diastolic, atrial) measured by tissue Doppler imaging, AP4C = apical 4-chamber view, E'$_{STE}$ = tricuspid annular velocity (diastolic, early) measured by speckle-tracking echocardiography, E'$_{TDI}$ = tricuspid annular velocity (diastolic, early) measured by tissue Doppler imaging, ME4C = mid-esophageal 4-chamber view, S'$_{STE}$ = tricuspid annular velocity (systolic) measured by speckle-tracking echocardiography, S'$_{TDI}$ = tricuspid annular velocity (systolic) measured by tissue Doppler imaging. The dotted line shows a line of perfect 1:1 correlation, while the solid line shows the regression line from the data.

TABLE 1

Variable	ICC, Interobserver	ICC, Intraobserver
Tissue Doppler-based velocities, AP4C		
S'_{TDI}, cm/s	0.95 (0.90 – 0.98)	0.99 (0.98 – 1.00)
E'_{TDI}, cm/s	0.85 (0.65 – 0.93)	0.97 (0.93 – 0.99)
A'_{TDI}, cm/s	0.87 (0.69 – 0.94)	0.99 (0.96 – 0.99)
Speckle-Tracking-based velocities, ME4C		
S'_{STE}, cm/s	*0.73 (0.38 – 0.88)*	*0.78 (0.57 – 0.90)*
E'_{STE}, cm/s	*0.72 (0.37 – 0.88)*	*0.57 (0.24 – 0.78)*
A'_{STE}, cm/s	*0.14 (0.00 – 0.62)*	*0.78 (0.57 – 0.90)*
Speckle-Tracking-based velocities, AP4C		
S'_{STE}, cm/s	*0.83 (0.60 – 0.93)*	*0.93 (0.82 – 0.97)*
E'_{STE}, cm/s	*0.72 (0.32 – 0.88)*	*0.50 (0.13 – 0.75)*
A'_{STE}, cm/s	*0.71 (0.29 – 0.88)*	*0.57 (0.22 – 0.80)*

Conventional measures are shown in regular font, and novel measures in italics.

<0.40 = poor, 0.40-0.59 = fair, 0.60-0.74 = good, >0.74 = excellent. Interrater reliability calculated using a two-way random effect model, mean of k-raters and absolute agreement (ICC(3,k)). Intrarater reliability calculated with a two-way mixed effects model, mean of k measurements, and absolute agreement (ICC(2,1)).