Guidance for accurate and consistent tissue Doppler velocity measurement: comparison of echocardiographic methods using a simple vendor-independent method for local validation

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Background

Variability has been described between different echo machines and different modalities when measuring tissue velocities. We assessed the consistency of tissue velocity measurements across different modalities and different manufacturers in an in vitro model and in patients. Furthermore, we present freely available software tools to repeat these evaluations.

Methods and results

We constructed a simple setup to generate reproducible motion and used it to compare velocities measured using three echocardiographic modalities: M-mode, speckle tracking, and tissue Doppler, with a straightforward, non-ultrasound, optical gold standard. In the clinical phase, 25 patients underwent M-mode, speckle tracking, and tissue Doppler measurements of s′, e′, and a′ velocities.

In vitro, the M-mode and speckle tracking velocities agreed with optical assessment. Of the three possible tissue Doppler measurement conventions (outer, middle, and inner edge) only the middle agreed with optical assessment (discrepancy −0.20 (95% CI −0.44 to 0.03) cm/s, P = 0.11, outer +5.19 (4.65 to 5.73) cm/s, P < 0.0001, inner −6.26 (−6.87 to −5.65) cm/s, P < 0.0001). A similar pattern occurred across all four studied manufacturers. M-mode was therefore chosen as the in vivo gold standard.

Clinical measurements of s′ velocities by speckle tracking and the middle line of the tissue Doppler showed concordance with M-mode, while the outer line overestimated significantly (+1.27 (0.96 to 1.59) cm/s, P < 0.0001) and the inner line underestimated (−1.82 (−2.11 to −1.52) cm/s, P < 0.0001).

Conclusions

Echocardiographic velocity measurements can be more consistent than previously suspected. The statistically modal velocity, found at the centre of the spectral pulsed wave tissue Doppler envelope, most closely represents true tissue velocity. This article includes downloadable, vendor-independent software enabling calibration of echocardiographic machines using a simple, inexpensive in vitro setup.

Keywords

Echocardiography • Tissue Doppler • Velocity • Calibration

Introduction

It has not been clear exactly where on the envelope of the pulsed Doppler spectral display is best to measure instantaneous tissue velocity.1–6 Moreover, different machines are said to give different velocities.7–10 The discrepancies are not trivial, especially in diseases that depress velocities. Worse, the same machine using the different modalities (e.g. tissue Doppler and M-mode) gives different velocities for the same structure in the same patient.

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Guideline recommendations could be read as advocating measuring the ‘outer edge of the dense (or bright) envelope of the spectral recording’. The clinical measurement practices that emerged can be seen in Figure 1 which shows examples from guidelines and teaching documents over the following years.

Clinical practice evades these discrepancies in two ways. First, conventional protocols avoid measuring the same velocity by two methods, so that the discrepancy goes unnoticed. Second, end-users expect their equipment for measuring quantities such as blood pressure or body weight to be calibrated rather than merely assumed to be correct. In contrast, we never ask whether echocardiographic systems for measuring velocity have been calibrated, even in the face of conflicts that are puzzling.

Available phantoms can measure blood velocity or distance, but tissue Doppler velocity calibration is less straightforward. We therefore developed a simple setup and used it to:

(i) investigate for consistent differences between tissue Doppler and M-mode derived measurements of tissue velocity,
(ii) evaluate the performance of speckle tracking-based tissue velocity measurements, and
(iii) decide where to make measurements on tissue Doppler traces.

We present detailed instructions on assembly, and downloadable analysis software in Supplementary data online, S1–S9.

**Methods**

**In vitro calibration of echocardiographic velocity measurements**

**Data acquisition**

The in vitro setup was designed with an ultrasound probe moving repeatedly toward and away from a tissue-mimicking phantom (see Supplementary data online, S1) at 10 separate velocities, from 10 to 20 cm/s. B-mode, M-mode, and pulsed wave tissue Doppler images of the phantom were recorded twice at each velocity. Each velocity was measured independently by automated optical tracking of a video recording of probe motion. This velocity was used as the gold standard because it was measured independently of any ultrasound components.

Automated peak velocity measurements were made from the M-mode and tissue Doppler traces (Figure 2). All the software used was developed in-house using Matlab (Mathworks Inc.) and is available upon request.

**Figure 1:** Current convention for measurement of tissue Doppler velocity as displayed in guidelines and teaching documents. Each panel has been reproduced from a different document: A12, B13, C14, D15, E16, F17, G18, H19, I20, J11, K21, and L22. In panels A, H, and L, we have added dashed horizontal lines marking the stated velocity value.
The tissue Doppler algorithm, for each column of the image, identifies the point of highest intensity and the outer and inner edges of the envelope. In this paper, we call the point of highest intensity (i.e. point of brightest white on the Doppler trace at any instant in time) the ‘middle’ for simplicity and to contrast it with the outer and inner edges. This point may be considered the statistically most frequent velocity, i.e. the velocity possessed by the largest quantity of reflective tissue. If the distribution of velocities is symmetrical, then this will be the same as the middle of the distribution. Care is needed with the term ‘modal’ velocity because there is a published definition of the term ‘modal’ which differs from the standard statistical meaning.11

Speckle tracking was performed on the B-mode cine loops using vendor-independent algorithms developed in-house. The speckle tracking algorithm uses a block-matching method with sum of absolute differences. The velocity vectors within the region of interest (automatically selected as a 50 × 70 pixel region in the centre of the image to capture the phantom motion) were averaged to obtain the velocity profile. Peak velocities were averaged across 4–6 ‘beats’ from the two acquisition repetitions at each tested velocity.

The experiment was performed using four different machines: GE Vivid I, Philips iE33, Toshiba Artida, and Siemens Acuson SC2000. Tissue Doppler, M-mode, and B-mode images were analysed with automated software as described above. This study was not a comparison of manufacturers’ equipment but rather a test of measurement convention.

Non-ultrasound automated optical velocity measurement
To provide a measure of velocity completely independent of all the ultrasound hardware, software, and concepts, we developed a simple piece of software for video recordings made on any smartphone or video capture device. We used an iPhone (Apple Inc.) to record the movements of the probe juxtaposed with a ruler. Our software (downloadable from Supplementary data online) permits automatic measurements of velocity against time from the .MOV video file. This allowed our phantom to be used across a variety of velocities without having to assume linearity of the actuator system.

Statistical analysis
The discrepancy in peak measurements between the reference non-ultrasound optical tracking and each of the other modalities was calculated for each of the 10 tested velocities. The differences for all tested velocities were compared across modalities using ANOVA. Where there was significant inhomogeneity, the individual modalities were compared with optical assessment using paired Student’s t-tests. Bland–Altman plots were also displayed for comparing each modality with optical.

Data are presented as difference in mean peak measurement from optical and 95% CI.

In vivo validation
Subjects
Twenty-five sequential patients (16 male) in sinus rhythm (a mixture of patients with normal hearts and those with disease, from the routine echocardiography program in our hospital) underwent M-mode, B-mode, and tissue Doppler imaging. The study was approved by the local research ethics committee and all patients provided written informed consent.

Data acquisition
M-mode, B-mode, and tissue Doppler traces were acquired at the septal and lateral annuli as per standard clinical guidelines. Each set of acquisitions was conducted twice. Measurements of septal and lateral s’, e’, and a’ were obtained from the M-mode and tissue Doppler traces using automated software (Figure 3). The M-mode tracing software uses a correlation-based method to follow each M-mode line across time, and averages the lines to obtain the overall M-mode trace. The tissue Doppler tracing algorithm scans each column of the image to identify the highest intensity point and edges of the envelope. The peak velocity measurements were averaged across 5–6 beats.

Speckle-tracked measurements of peak s’, e’, and a’ of the B-mode images were obtained using the automated software as for the in vitro images. The peak velocities within the region of interest (30 × 50 pixel region at the annuli, around the regions of highest velocity) were averaged across 5–6 beats.

Figure 2: Representative automated M-mode (pink) and tissue Doppler outer (red), middle (blue), and inner (purple) traces obtained for one of the tested velocities using GE Vivid I.
Statistical analysis

In vivo, M-mode was the gold standard because optical tracking was not possible. Difference in peak measurement between M-mode and the other modalities was calculated for each patient. The differences for all patients were compared across modalities using ANOVA and where there was significant inhomogeneity, individual modalities were compared against M-mode using paired Student’s t-tests. Bland–Altman plots were displayed for comparing each modality with M-mode.

Reproducibility

Scientific findings can only be considered reliable if experimental results are reproducible in independent hands. To help this we provide:

Hardware
- Details of where examples of all equipment may be purchased, with total cost of <€1200.
- Assembly instructions.

Software
Downloadable software for any reader’s echocardiographic system for:
- vendor-independent quantification of M-mode recordings
- vendor-independent quantification of pulse-wave Doppler recordings
- vendor-independent quantification of speckle-tracked tissue velocities
Downloadable software for any reader’s video capture device (e.g. camera phone) for:
- vendor-independent quantification of velocity by optical tracking

Results

In vitro calibration of echocardiographic velocity measurements

Using the in vitro model, the M-mode, speckle tracking, and tissue Doppler (middle line) traces broadly agreed with non-ultrasound optical assessment. Figure 4 shows a representative example of the M-mode, speckle tracking, and tissue Doppler (outer, middle, and inner line) traces overlaying the optical trace. All raw traces are available from the authors.

Peak velocity measurements from the four tested manufacturers showed a similar relationship between M-mode, speckle tracking, and tissue Doppler (outer, middle, and inner lines) against optical (Figure 5). M-mode and speckle tracking peak measurements were concordant with optical and of the three tissue Doppler conventions (outer, middle, and inner line) only the middle line agreed with optical. The outer line significantly overestimated and the inner line significantly underestimated velocity (discrepancy using GE Vivid I: outer = +5.19 (95% CI 4.65 to 5.73) cm/s, P < 0.0001, inner = -6.26 (-6.87 to -5.65) cm/s, P < 0.0001). For all four manufacturers, Bland–Altman analysis (Figure 6) showed agreement between M-mode, speckle tracking, and the middle line of tissue Doppler against non-ultrasound optical assessment. The outer line overestimated and the inner underestimated velocities. The biases between each modality and optical are summarized in Table 1.

ANOVA confirmed the disagreement between modalities (GE Vivid I P < 0.0001). Individual Student’s t-tests showed that there was a significant difference between the optical and the outer and inner Doppler lines (P < 0.0001). There was no significant difference in peak measurements between the optical and M-mode (P = 0.16), speckle tracking (P = 0.27), and the middle tissue Doppler value (P = 0.11). Peak measurements using different manufacturer equipment showed similar results.

Figure 7 shows the peak measurement at each velocity across manufacturers using the outer, middle, and inner line. The distribution of peak velocity measurement across manufacturers using the outer tissue Doppler line was 1.57 (0.58 to 2.57) cm/s, middle 0.58 (0.22 to 0.96) cm/s, and inner 1.01 (0.37 to 1.66) cm/s.

In vivo measurements

Septal annulus measurements showed concordance between M-mode, speckle tracking, and tissue Doppler middle line. Figure 8 shows representative speckle tracking and tissue Doppler (outer,
**Figure 4:** M-mode (pink), speckle tracking (green), and tissue Doppler outer (red), middle (blue), and inner (purple) traces overlaying the corresponding non-ultrasound optical tracking trace (gray) for one of the tested velocities using GE Vivid I.

**Figure 5:** Comparison of peak measurement using optical tracking, M-mode (pink square), speckle tracking (green cross), and tissue Doppler (outer line (red dot), middle line (blue dot), inner line (purple dot)) for the 10 tested velocities using GE Vivid I Philips iE33, Toshiba Artida, and Siemens SC2000.
middle, and inner line) traces overlaying the M-mode trace, for one patient. Peak measurements from speckle tracking and tissue Doppler middle line were concordant with M-mode (Figure 9).

Peak velocity measurements from the outer line of tissue Doppler overestimated (1.27 (0.96 to 1.59) cm/s, $P < 0.0001$) and the inner underestimated ($-1.82 (-2.11 to -1.52)$ cm/s, $P < 0.0001$).

Table 1  Average Bland–Altman biases in peak velocity measurements (cm/s) across 10 tested velocities and four manufacturers (GE, Philips, Toshiba, and Siemens) using M-mode, speckle tracking, and tissue Doppler (outer, middle, and inner line) compared against non-ultrasound optical assessment, shown with 95% CIs

<table>
<thead>
<tr>
<th>Manufacturer</th>
<th>M-mode</th>
<th>Speckle tracking</th>
<th>Tissue Doppler</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>Outer line</td>
</tr>
<tr>
<td>GE Vivid I</td>
<td>0.06(-0.02 to 0.15)</td>
<td>0.19(-0.13 to 0.51)</td>
<td>5.19(4.65 to 5.73)</td>
</tr>
<tr>
<td></td>
<td>$P = 0.16$</td>
<td>$P = 0.27$</td>
<td>$P &lt; 0.0001$</td>
</tr>
<tr>
<td>Philips iE33</td>
<td>0.13(-1.31 to 1.56)</td>
<td>0.13(-0.15 to 0.4)</td>
<td>3.46(3.14 to 3.78)</td>
</tr>
<tr>
<td></td>
<td>$P = 0.59$</td>
<td>$P = 0.38$</td>
<td>$P &lt; 0.0001$</td>
</tr>
<tr>
<td>Toshiba Artida</td>
<td>$-0.66(-1.24 to -0.07)$</td>
<td>$-0.35(-0.56 to -0.14)$</td>
<td>7.57(6.82 to 8.33)</td>
</tr>
<tr>
<td></td>
<td>$P = 0.05$</td>
<td>$P = 0.10$</td>
<td>$P &lt; 0.0001$</td>
</tr>
<tr>
<td>Siemens SC2000</td>
<td>$-0.18(-0.33 to -0.03)$</td>
<td>$-0.37(-0.73 to -0.01)$</td>
<td>5.26(4.73 to 5.78)</td>
</tr>
<tr>
<td></td>
<td>$P = 0.04$</td>
<td>$P = 0.07$</td>
<td>$P &lt; 0.0001$</td>
</tr>
</tbody>
</table>

Figure 6: Modified Bland–Altman plots showing M-mode (pink square), speckle tracking (green cross), tissue Doppler (outer line (red dot), middle line (blue dot), and inner line (purple dot)) compared against non-ultrasound optical tracking for the 10 tested velocities using GE Vivid I, Philips iE33, Toshiba Artida, and Siemens SC2000. Each vertical bar shows the bias (middle horizontal line) and the limits of agreement, i.e. ±2SD (upper and lower horizontal lines).
The different modalities disagreed with each other (ANOVA, $P < 0.0001$), but individual Student's $t$-tests showed that this was caused by the outer and inner lines of the tissue Doppler trace (outer and inner $P < 0.0001$). There was no significant difference between M-mode and speckle tracking ($P = 0.12$). Between M-mode and the middle of the tissue Doppler trace there was a small difference which met the criteria for statistical significance ($P = 0.04$).

The lateral annulus showed the same pattern. The M-mode, speckle tracking, and middle tissue Doppler measurements were concordant, while the outer line of tissue Doppler significantly over-estimated the peak and the inner line significantly underestimated it (Figure 9).

Discrepancy between the modalities was confirmed by ANOVA ($P < 0.0001$), and individual Student's $t$-tests showed that this was...
caused by the outer and inner lines of the tissue Doppler (outer and inner \( P < 0.0001 \)). No significant difference was observed between M-mode and speckle tracking \( (P = 0.07) \) and between M-mode and the middle line of the tissue Doppler there was a small but statistically significant difference \( (P = 0.05) \).

Bland–Altman analysis (Figure 10) showed agreement between speckle tracking and the tissue Doppler middle line against M-mode, not shared by the outer and inner lines of tissue Doppler. The biases between each modality and M-mode for septal and lateral \( s' \) measurements are summarized in Table 2.

**Discussion**

In this study, we describe a simple method for calibrating echocardiographic measurements. Our application of this approach showed that the clinical standard for defining tissue velocity by M-mode and by speckle tracking is correct. However, the current guideline recommendations for tissue Doppler velocity measurements (Figure 1) appear to cause overestimation.

Figure 9: Comparison of septal and lateral \( s' \) measurement using M-mode (x-axis), speckle tracking (green cross), and tissue Doppler (outer (red dot), middle (blue dot), and inner line (purple dot)) across 25 patients.  

Figure 10: Modified Bland–Altman plots showing septal and lateral \( s' \) measurements using speckle tracking (green), tissue Doppler outer (red), middle (blue), and inner (purple) compared against M-mode for 25 patients. Each vertical bar shows the bias (middle horizontal line) and the limits of agreement, i.e. ±2SD (upper and lower horizontal lines).

Traditional guidance for tracing of Doppler envelopes is to draw around the outer margin,\(^{11-22} \) i.e. the ‘peak’ (in the sense of greatest instantaneous velocities) and then to measure the ‘peak’ (in the sense of the highest velocity during one cardiac cycle). The extent to which instantaneous peak velocity exceeds instantaneous mean velocity depends on the thickness of the Doppler envelope and human judgement of the outer margin (Figure 11). It is affected by sweep speed, region of interest, gain and filter settings. Only Doppler line thickness of one pixel would resolve this problem definitively.

Until then, an easy yet accurate convention might be to measure the instantaneous brightest point on the trace, which we have denoted in this report for simplicity the ‘middle’. This is the statistically ‘modal’ velocity which should correspond to the velocity of the largest quantity of echo-reflecting tissue within the sample volume. Our automated algorithm identifies the brightest point at each time on the spectral trace. In this paper, we refer to this as the ‘middle’ line on the spectral Doppler trace to clearly distinguish it from the outer and inner edges. We should remember that the statistically ‘modal’ velocity may not necessarily lie exactly in the middle of the trace envelope, in situations where the distribution of velocities is asymmetrical. A fuller description would be the ‘the line joining the points of greatest intensity from each instant in time’. 
We have avoided the term ‘modal’ in the main manuscript to minimize inclarity. Although the statistical definition as the most frequent velocity (brightest point) is unambiguous,11 clinical habit has favoured measurement at an outer edge without necessarily realizing this is different (Figure 1).11–22 The term ‘middle’ is easily understood and translated, and difficult to misinterpret.

Regardless of the age of the machine we tested (none of which had previously undergone a velocity calibration in the hospital), the middle of the tissue Doppler trace is closely concordant with M-mode velocity, speckle-tracked velocity, and ruler-and-stopwatch direct observation. This is not suggestive of a drift in calibration with time. Rather, it suggests that the advice to read the outer extreme of a velocity trace has always been incorrect.

**Potential advantages of more transparency**

If manufacturers routinely provided open details of how the Doppler traces were derived, and guideline authorities habitually published details of replicable laboratory experiments upon which recommendations are made, it would be more straightforward to interpret findings of studies such as ours.

**Systematic errors that may be concealed within commercial systems**

Secrecy around analysis algorithms is never helpful because it prevents our community recognizing faulty measurement methodology. Mårtensson et al. present an elegant analysis of multiple ultrasound hardware and analysis systems.32 Of the systems they analysed, they found that one showed excellent tracking of true displacement, while another showed extensive tracking failure, giving artefactual positive displacements during zero displacement phases. The remaining systems appeared to have a range of subtle to dramatic upward biases, which grew progressively with duration of the recordings.

A similar result was observed with velocity measurements, with one system failing to track zero velocity phases. The systems which showed significant bias in displacement tracking overestimated peak velocities by 34%, but using a different machine of the same model overestimated velocities by only 6%. They concluded that displacement and velocity measurements could differ significantly depending on the machine or analysis software, and how the manufacturer has implemented the theory behind the measurement. The algorithms used for measurements are currently not openly available from the manufacturers.

Our study uses methods that are open to inspection and improvement. Its results show concordance between manufacturers and between modalities.

**Study limitations**

In patients, it is not possible to measure the same beat using multiple modalities, and measuring different beats with different methodologies runs the risk of discrepancy due to biological variability,33 rather than the measurement algorithms being discrepant. To reduce the effect of this variability, we conducted each acquisition twice and averaged peak velocity measurements across acquisitions and multiple beats.

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**Table 2** Average Bland–Altman biases across 25 patients of septal and lateral s’ velocity measurements (cm/s) in vivo using speckle tracking and tissue Doppler (outer, middle, and inner line) compared against M-mode, shown with 95% CIs

<table>
<thead>
<tr>
<th>Measurement</th>
<th>Speckle tracking</th>
<th>Tissue Doppler</th>
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<tbody>
<tr>
<td></td>
<td>Outer line</td>
<td>Middle line</td>
</tr>
<tr>
<td>Septal</td>
<td>s’ 0.26 (−0.06 to 0.59)</td>
<td>1.27 (0.96 to 1.59)</td>
</tr>
<tr>
<td></td>
<td>P = 0.12</td>
<td>P &lt; 0.0001</td>
</tr>
<tr>
<td></td>
<td>e’ −0.14 (−1.59 to 1.3)</td>
<td>1.22 (0.80 to 1.65)</td>
</tr>
<tr>
<td></td>
<td>P = 0.32</td>
<td>P &lt; 0.0001</td>
</tr>
<tr>
<td></td>
<td>a’ −0.03 (−0.35 to 0.3)</td>
<td>2.01 (1.72 to 2.30)</td>
</tr>
<tr>
<td></td>
<td>P = 0.87</td>
<td>P &lt; 0.0001</td>
</tr>
<tr>
<td>Lateral</td>
<td>s’ −0.41 (−0.84 to 0.02)</td>
<td>1.35 (1.01 to 2.09)</td>
</tr>
<tr>
<td></td>
<td>P = 0.07</td>
<td>P &lt; 0.0001</td>
</tr>
<tr>
<td></td>
<td>e’ −0.12 (−0.44 to 0.21)</td>
<td>1.98 (1.43 to 2.54)</td>
</tr>
<tr>
<td></td>
<td>P = 0.48</td>
<td>P &lt; 0.0001</td>
</tr>
<tr>
<td></td>
<td>a’ 0.12 (−0.5 to 0.74)</td>
<td>2.43 (1.87 to 2.98)</td>
</tr>
<tr>
<td></td>
<td>P = 0.70</td>
<td>P &lt; 0.0001</td>
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</table>
For the patient studies, we have used M-mode as the ‘gold standard’ to assess the validity of different modalities. Since there is no method to obtain an independent measurement, we consider this an acceptable assumption offering minimal assumptions (requiring only time and distance calibration to be correct) and agreement with non-ultrasound optical assessments from in vitro studies.

Raw B-mode data from the machines is in proprietary format, whose details are not available. We therefore used uncompressed DICOM data for speckle tracking. We found that although the acquired frame rate was >50 Hz, there were cases where frame rate dropped (≈30–40 Hz) when data were exported as DICOM, resulting in sub-optimal speckle tracking. This was resolved by averaging across multiple beats. We hope manufacturers may in future volunteer, or be forced, to reveal the formats in which the machines we purchase are storing our patients’ data.

**Conclusion**

We test echocardiographic velocity measurements from different manufacturers in multiple modalities (M-mode, speckle tracking, and tissue Doppler) against an ultrasound-independent standard of optical tracking. We present our software tools freely to assist independent replication.

Our *in vitro* results and patient studies show that the middle of the tissue Doppler trace gives velocity measurements that are consistent with the other ultrasound modalities as well as an entirely independent optical assessment. The middle line is also the most reproducible between manufacturers. Echocardiographers who think it desirable to assess the validity of different modalities. Since there is no agreement an acceptable assumption offering minimal assumptions (requiring method to obtain an independent measurement, we consider this.


