Generation of ultra-realistic synthetic ultrasound images to facilitate standardization of deformation imaging

Context

- 3D Speckle tracking (3D-STE) tools available for (semi-) automatic analysis of cardiac dynamics (deformation/strain);
- Major vendors of US equipment provide 3D-STE based suites (TomTec, Toshiba, Philips, Siemens);
- Clinical feasibility for detecting conditions as ischemia and dyssynchrony;

[Mor-Avi et al. EHJ, 2011]
Reproducibility and Inter-Vendor Variability of Left Ventricular Deformation Measurements by Three-Dimensional Speckle-Tracking Echocardiography

Etienne Gayat, MD, MSc, Homaa Ahmad, MD, Lynn Weinert, BS, RDCS, Roberto M. Lang, MD, and Victor Mor-Avi, PhD, Chicago, Illinois; Paris, France

**Background:** Myocardial deformation measurements using two-dimensional speckle-tracking echocardiography (STE) are known to vary among vendors. The intervendor agreement of three-dimensional (3D) deformation indices has not been studied. The goals of this study were to determine the intervendor agreement of 3D STE–based measurements of left ventricular (LV) deformation parameters to investigate the intrinsic variability of these measurements and identify the sources of intervendor differences.

**Methods:** Real-time full-volume images obtained in 30 subjects with normal LV systolic function using two vendors’ equipment (V1 and V2) on the same day were analyzed by two independent observers using two software packages (S1 and S2). Agreement between three technique combinations (V1/S1, V2/S2, and V1/S2) and their intrinsic reproducibility (interobserver and intraobserver agreement) were assessed using intraclass correlation coefficients. Parameters of LV deformation included global longitudinal strain, twist, 3D displacement, and 3D strain and its radial, longitudinal, and circumferential components.

**Results:** For all three combinations, intertechnique agreement was poor (intraclass correlation coefficient < 0.4), always beyond the intrinsic variability. For all measured parameters, the intertechnique agreement was better when the same software package was used with images from different vendors (V2/S2 vs V1/S2) than when images from same vendor were analyzed using different software (V1/S2 vs V1/S1).

**Conclusions:** Three-dimensional STE–derived LV deformation parameters are highly vendor dependent, and the discordance levels are beyond intrinsic measurement variability of any of the tested combinations of imaging equipment and analysis software. This intervendor discordance must be taken into account when interpreting 3D deformation data. (J Am Soc Echocardiogr 2011;24:878-85.)

**Keywords:** Three-dimensional echocardiography, Speckle tracking, Ventricular function
Definition of a **rigorous protocol for quality assessment of 3D-STE** (consensus on definitions and tools)
Evaluation of 3D-STE

Reliability of the reference displacement

Level of realism of the data set

In silico

In vitro

In vivo - animals

In vivo - humans

Ideal reference

[courtesy Jan D’hooge]
Evaluation of 3D-STE

In silico

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In silico

In vitro

piezoelectric crystals

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All Levels have benefits and require attention

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Previous standardization efforts

Geometrical Model

Kinematic model

Ultrasound simulation environment

Truncated Ellipsoid

Distribute scatterers
Simulate point spread function US

Gao et al., T-UFFC, 2009

[courtesy Brecht Heyde]
Previous standardization efforts

• Used in EACVI/ASE co-promoted task force for standardization of GLS from 2D US;

• **Limited realism:**
  - Kinematic model;
  - No surrounding structures;
  - Homogeneous intensity in the myocardium;

[courtesy Brecht Heyde]
Improving the kinematic model...

**Realistic anatomy**
*(segmentation of MRI recording)*

\[ \text{[Marchesseau et al., BMMB, 2012]} \]

<table>
<thead>
<tr>
<th>Notation</th>
<th>Parameter name</th>
<th>Min–Max</th>
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<tbody>
<tr>
<td>( \sigma_0 ) (MPa)</td>
<td>Max contraction</td>
<td>4–10</td>
</tr>
<tr>
<td>( k_0 ) (MPa)</td>
<td>Max stiffness</td>
<td>3–9</td>
</tr>
<tr>
<td>( k_{\text{ATP}} ) (s(^{-1}))</td>
<td>Contraction rate</td>
<td>5–20</td>
</tr>
<tr>
<td>( k_{\text{RS}} ) (s(^{-1}))</td>
<td>Relaxation rate</td>
<td>5–60</td>
</tr>
<tr>
<td>( E_s ) (MPa)</td>
<td>Linear modulus</td>
<td>3–15</td>
</tr>
<tr>
<td>( \alpha )</td>
<td>Cross-bridges unfasten rate</td>
<td>0–0.8</td>
</tr>
<tr>
<td>( \mu ) (MPa s)</td>
<td>Viscosity</td>
<td>0.07–0.6</td>
</tr>
<tr>
<td>( c_1, c_2 ) (kPa)</td>
<td>Mooney Rivlin modulus</td>
<td>7–20</td>
</tr>
<tr>
<td>( K ) (MPa)</td>
<td>Bulk modulus</td>
<td>6–25</td>
</tr>
<tr>
<td>( \tau ) (s)</td>
<td>Wind. charact. time</td>
<td>0.4–2</td>
</tr>
<tr>
<td>( R_p ) (MPa m(^{-3}) s)</td>
<td>Wind. periph. resistance</td>
<td>30–300</td>
</tr>
<tr>
<td>( Z_c ) (MPa m(^{-3}) s)</td>
<td>Wind. charact. resistance</td>
<td>1–10</td>
</tr>
<tr>
<td>( L ) (kPa s(^2) m(^{-3}))</td>
<td>Wind. total art. inertance</td>
<td>1–100</td>
</tr>
</tbody>
</table>
Improving the kinematic model...

Modify contractility and stiffness

Electromechanical model

Marchesseau et al., BMMB, 2012

[courtesy Brecht Heyde]
Improving the kinematic model...

Modify early activation areas

Partial LBBB

LBBB

Electromechanical model

Marchesseau et al., BMMB, 2012

[courtesy Brecht Heyde]
Improving the kinematic model...

Anatomical model → Electromechanical model → Ultrasound simulation environment

- Obtained from MR segmentation
- Normal contractility, activation
- Distribute scatterers, simulate point spread function US

[De Craene et al., 2013]
Improving the kinematic model...

- Benchmark academic algorithms [STACOM, Nice, 2012], [DeCraene et al., Trans Med Imaging, 2013];
- **Visual realism still limited:**
  - No surrounding structures;
  - No US artifacts that might affect STE.
Proposed Framework

1. **Anatomical model**
2. **Electromechanical model**
3. **Ultrasound simulation environment**

- Model for texture
- Real recording
- Simulated sequence
• Visually realistic:
  o *Surrounding structures*;
  o *US artifacts (dropout, reverberation, clutter, ...)*;
Simulated sequences

- Visually realistic:
  - Surrounding structures;
  - US artifacts (dropout, reverberation, clutter, ...);
- Still synthetic:
  - Cardiac motion exactly known (E/M model);
  - Real recording works ONLY as template for echogenicity (no influence on motion);
Method: Visual Aspect

- Tissue as collection of **point scatterers** with given position and amplitude;
- Scattering amplitude sampled from the real clinical recording (template):

![Diagram of ultrasound simulation process]

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**Template frame**

**Scatter map generation**

**Ultrasound Simulation**

COLE [Gao et al.]
Method: Motion

**Inside the myocardium:**

- Coherent motion established by E/M model \(\Rightarrow\) speckle coherency
**Method: Motion**

**Inside the myocardium:**
- Coherent motion established by E/M model \(\Rightarrow\) speckle coherency

**Outside the myocardium:**
- Random motion of scatterers \(\Rightarrow\) incoherent speckle (blood);
- Amplitude sampled from template frame at the corresponding instant in the cardiac cycle \(\Rightarrow\) surrounding structures.
- Need of spatio-temporal matching the two data-sets.
Simulated Sequences: Ultrasound Properties

Realistic Speckle Statistics

Realistic Temporal Coherency
Simulated Sequences: Mechanical Properties

- E/M model allows simulating healthy and pathological cases;

**Healthy**

- **radial**
  - NORMAL RANGE* [35.1%; 59%]

- **circumferential**
  - NORMAL RANGE* [-20.9%; -27.8%]

- **longitudinal**
  - NORMAL RANGE* [-15.9%; -22.1%]

*[Yingchoncharoen et al, JASE 2013]*
Simulated Sequences: Mechanical Properties

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*Yingchoncharoen et al, JASE 2013*
Myocardial Infarction

Simulated Sequences: Mechanical Properties

**Normal**

**LCX**

**RCA**

**LAD prox**

**LAD dist**
Simulated Sequences: Mechanical Properties

**Myocardial Infarction**

**Normal**

- Healthy - Circ ES Strain
- LAD prox - Circ ES Strain
- LAD dist - Circ ES Strain

**LCX**

- LCX - Circ ES Strain
- LCX prox - Circ ES Strain
- LCX dist - Circ ES Strain

**RCA**

- RCA - Circ ES Strain
- RCA prox - Circ ES Strain
- RCA dist - Circ ES Strain

**Dyssynchrony (LBBB)**

- Late wall
- Septum

[De Craene et al., TMI, 2013]
Conclusion

• Novel pipeline based on ultra-realistic synthetic sequences for the QA of 3D-STE;
• Level of realism of existing techniques highly improved both in terms of visual aspect and motion;
• A library of sequences will be created, including healthy and pathological cases (LAD, LCX, RCA, LBBB);
• The sequences will be made freely accessible by the research community;
• Future developments include:
  o *Comparison of STE techniques (academic and hopefully vendors)*;
  o *Improve the E/M simulations to obtain more consistent reference strain values (longitudinal in particular)*;
  o *Improve the ultrasound simulator for non-standard beam-forming techniques (Plane waves, MLT, Shear waves, ...)*.
Thank you for your attention

For any questions
martino.alessandrini@uzleuven.be
Evaluation of 3D-STE

Reliability of the reference method

- **In silico**
- **In vitro**
- **In vivo - animals**
- **In vivo - humans**

Level of realism of the data set

[courtesy Jan D’hooge]