34th Annual International Conference of the IEEE EMBS
San Diego, California USA, 28 August - 1 September, 2012

Impact of Temporal Resolution on LV Myocardial Regional Strain Assessment with Real-Time 3D Ultrasound

Auranuch Lorsakul, *Student Member, IEEE,* Viktor Gamarnik, *Student Member, IEEE,* Qi Duan, *Member, IEEE,* Cesare Russo, Elsa Angelini, *Senior Member, IEEE,* Shunichi Homma, and Andrew F. Laine, *Fellow, IEEE*

Abstract— **Non-invasive quantification of regional left ventricular (LV) deformation is crucial for the identification of clinical and subclinical myocardial dysfunction in various conditions. Several software tools now exist to provide regional LV strain estimation for echocardiography images. In this paper, we experimentally investigated the impact of real-time three-dimensional (RT3D) ultrasound temporal resolution on the precision of an integrated speckle-tracking framework. We compared temporal displacement and strain profiles acquired at three different frame rates on five normal volunteers. Results showed that estimated displacement fields and regional strain measurements were more homogeneous and of larger amplitude at higher frame rates.**

I. Introduction

Ultrasound (US) is frequently used as the first screening modality when there is suspicion of many cardiac conditions. Although not yet part of routine clinical care, cardiac strain analysis with 3D echocardiography is gaining in maturity and sophistication due to development of novel methods. There is considerable potential in measuring the full set of strains, because some subset of them may form a good predictor for LV dysfunction or disease prognosis [1]. Analysis of LV deformation using speckle-tracking permits quantitative description of function by eliminating most subjective user-dependent factors. This approach is useful in some clinical settings, particularly in patients with heart failure, to assess LV dyssynchrony and to reduce the rate of non-response to Cardiac Resynchronization Therapy (CRT)—though analysis is limited to 2D echocardiograms [2] and only few studies in 3D echocardiography. In general clinical practice, 2D speckle-tracking strain analysis remains the standard because it has been much more extensively validated both in technical and clinical research; however, temporal resolution directly affects the veracity of the underlying working assumption of in plane motion between two time frames. Performing 3D rather than 2D speckle tracking remains of value because it provides a more realistic tracking of cardiac tissue motion. Nonetheless, there is an open issue of identifying the minimal temporal resolution (or frame rate (FR)) required for accurate strain measures on echocardiographic images.

We have previously developed semi-automated image analysis tools [3] that can provide regional strain measures from RT3D ultrasound data. This framework involves some dedicated denoising, that was optimized on the clinical data in [4], and correlation-based speckle tracking. We have shown that the LV strain estimations based on speckle tracking were quantitatively comparable to sonomicrometry (a standard invasive ground truth) in tracking regional deformation. Nevertheless, it appears clearly that at 25 Hz, the sampling rate was too slow to capture fast contraction patterns, which are visible with sonomicrometry. Several studies [5, 6] have examined frame rate effects on speckle tracking in the setting of cardiac imaging. Other studies [7, 8] have evaluated positively the capacity of speckle-tracking to characterize LV deformation with standard clinical RT3D ultrasound probes. Nevertheless, these studies presented only partial validation for selective strain measures (either longitudinal or radial).

The goal of this study is to investigate the influence of RT3D ultrasound temporal resolution on our speckle-tracking framework, for all strain components. For RT3D screening, the frame rate can be increased at the cost of reducing the number of scan lines and/or the field of view (FOV). Both scanning parameters have an impact on the spatial resolution which trades off with temporal resolution. In this study, we propose to identify experimentally the minimal frame rate that should be used to perform accurate strain analysis on healthy volunteers, using a standard clinical probe.

II. Method

To quantify LV strain from volumetric RT3D echocardiographic images we rely on a previously designed framework consisting of the following processing pipeline: 1) image denoising; 2) region of interest (ROI) segmentation to initialize the speckle tracking; 3) speckle tracking with cross-correlation used as the image similarity metric, to estimate a dense 3D displacement field; and 4) Lagrangian strain measures in natural coordinates, to assess the three strain components: longitudinal, radial and circumferential.

*Research supported by the National Heart, Lung and Blood Institute, NIH, Grant No. 5R01HL086578.

A. Lorsakul and V. Gamarnik are with the Department of Biomedical Engineering, Columbia University, ET-351, 1210 Amsterdam Avenue, New York, NY 10027, USA (e-mail: al2776 and vg2125@columbia.edu).

Q. Duan, Ph.D is with NINDS, NIH, 10 Center Dr, Bethesda, MD 20892 (e-mail: Qi.Duan@nih.gov).

E. D. Angelini, Ph.D is with Institut Telecom, Department of Image and Signal Processing, Telecom ParisTech, CNRS LTCI, 46 rue Barrault, 75013, Paris, France (e-mail: elsa.angelini@telecom-paristech.fr).

S. Homma, M.D and C. Russo, M.D., are with the Division of Cardiology, Columbia University Medical Center, New York, NY 10027 USA (e-mail: sh23 and cr2321@columbia.edu).

A. F. Laine, D.Sc is with the Department of Biomedical Engineering and Radiology, Columbia University, New York, NY 10027, USA (corresponding author to provide phone: 212-854-5996; fax: 212-854-5995; e-mail: laine@columbia.edu).

A. Denoising and ROI Segmentation

Denoising, based on anisotropic diffusion, is first applied to improve the RT3D image quality, enhancing myocardial tissue homogeneity [4, 9]. Then a ROI is selected around the myocardium, via LV segmentation. In this study, a cardiologist manually traced the endocardial and epicardial surfaces at end-diastole (ED), in a parasternal short-axis view (SAX PM), an apical 4-chamber view (A4C), and an apical 2-chamber view (A2C) [10]. A complete myocardial mask was then created from these manual contours [11], as illustrated in Fig. 1. Speckle tracking was then run on all pixels within the myocardial mask to perform *point-wise* tracking throughout the whole cardiac cycle.

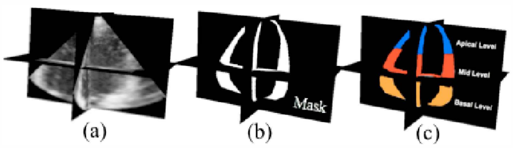

Figure 1. Orthogonal slices of: (a) a RT3D US dataset, (b) the myocardial binary mask, and (c) the AHA 16 segments partition of the LV.

B. Speckle Tracking

A 3D dense displacement field composed of vectors $[u(x, y, z), v(x, y, z), w(x, y, z)]$ is computed for each pair of consecutive RT3D volumetric frames. Point-wise 3D template-matching is performed based on the maximization of the cross-correlation coefficient (CC) between image I_t and I_{t+1} defined by the following equation:

$$CC = \frac{\sum_{x\in\Omega}\left(I_t(\mathbf{x})I_{t+1}(\mathbf{x}+\Delta\mathbf{x})\right)}{\sqrt{\sum_{x\in\Omega}I_t^2(\mathbf{x})\sum_{x\in\Omega}I_{t+1}^2(\mathbf{x}+\Delta\mathbf{x})}}, \tag{1}$$

where $\Delta\mathbf{x}$ is the displacement vector for each pixel in a small neighborhood Ω around a pixel $\mathbf{x}$. The neighborhood patch size Ω was defined as a $(7\times7\times7)$ cube centered around $\mathbf{x}$. Each voxel is tracked within a search cube of size $(9\times9\times9)$. These template and search sizes were experimentally selected as the optimal values from our recent study in [4]. The estimated displacement field was then spatially regularized using cubic splines polynomial fitting and local smoothing to enhance spatial coherence of the displacements.

C. Continuous-Time Myocardial Motion Analysis

Following the method described in [12], spatial gradients of the displacement field were computed to obtain individual strain components and the Lagrangian strain tensor defined as:

$$E = 1/2\left(\nabla u + \nabla u^T + \nabla u^T \nabla u\right) \tag{2}$$

Apical, basal, and mid-septal positions were defined manually for each subject, at ED, to align the displacement coordinate axis with the natural axis of the LV under study and therefore access longitudinal, radial and circumferential strain components. Dense displacement and strain values were spatially averaged using the 16-segment model of the LV myocardium prescribed by the American Society of Echocardiography (ASE) [13].

III. Experimental Results

A. Ultrasound Acquisition

Full RT3D volumetric images were acquired using an iE33 system with a matrix phased-array X5-1 probe (Philips Healthcare, Andover, MA). Images were acquired with ECG gating, and 4 sub-volume aggregation. Five healthy volunteers were screened for this study at the Columbia University Medical Center. For each volunteer, three RT3D US volumes were acquired at different temporal resolutions, via setting the frame rate to the following values: low (15Hz), medium (25Hz), and high (35Hz). The cardiologist reduced the FOV of the volumetric images to reach higher frame rates while preserving (as much as possible) the spatial resolution and still visualizing the whole LV. The spatial resolution had to be reduced as frame rate was increased, but remained below 1.2 mm^3 per voxel. Images were all normalized on the range of intensity values [0 255].

The dataset information, including the frame rate, the denoising parameter λ_0, the number of volumes per cardiac cycle (n), the RT3D US volume dimensions, and the spatial resolutions are reported in Table I for the 5 volunteers.

TABLE I. RT3D Ultrasound Dataset Information

Vol. #	*Frame Rate (Hz)*	λ_0	*n*	*Matrix Dimension (x,y,z)*	*Spatial Resolution (mm)*
1	15	8	18	(224,160,208)	(0.93,0.69,0.53)
	25	8	24	(240,176,208)	(0.78,0.62,0.53)
	35	7	42	(192,176,208)	(0.82,0.65,0.48)
2	15	8	14	(208,176,208)	(0.78,0.62,0.53)
	25	8	27	(208,176,208)	(0.92,0.70,0.53)
	35	6	32	(208,144,208)	(0.95,0.72,0.53)
3	15	7	14	(272,208,208)	(0.96,0.76,0.67)
	25	7	23	(256,176,208)	(0.99,0.75,0.68)
	35	7	38	(160,144,224)	(1.39,1.08,0.77)
4	15	6	15	(272,224,208)	(0.92,0.69,0.63)
	25	6	24	(224,176,208)	(0.93,0.70,0.63)
	35	8	36	(192,144,208)	(1.12,0.85,0.63)
5	15	7	17	(288,224,208)	(0.84,0.64,0.58)
	25	7	25	(224,176,208)	(0.85,0.68,0.58)
	35	5	40	(192,144,208)	(1.03,0.81,0.58)

λ_0 = denoising parameter, n = number of volumes/cardiac cycle

B. Data and Preprocessing

We used anisotropic diffusion to reduce image noise and increase tissue homogeneity prior to motion estimation using speckle tracking. Anisotropic diffusion relies on a gradient threshold parameter (λ_0) which was studied in [4]. Values of this threshold parameter for the different datasets are reported in Table I. A series of original RT3D US images and their denoised counterparts is illustrated in Fig. 2, where we can visually appreciate the degradation of the image quality as the frame rate increases.

B. Displacement Field

The displacement fields computed by our point-wise speckle tracking method generated components with larger amplitudes of motion and more homogeneous directions at higher frame rates. Fig. 3 shows that cumulative displacement fields obtained from direct speckle tracking between end-diastole (ED) and end-systole (ES) at the low, medium, and high frame rates. We can observe that the inward contracting motion of the myocardium muscle is more clearly observable on the high-frame rate dataset.

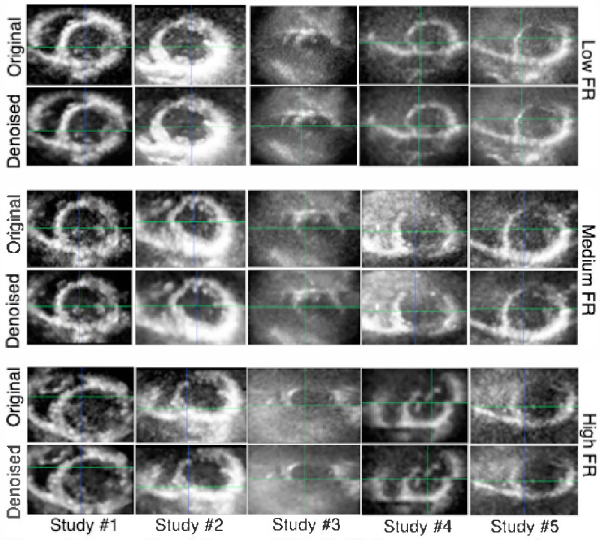

Figure 2. Original and denoised RT3D US images on the 5 volunteers at three different frame rates: low (15 Hz), medium (25 Hz), and high (35 Hz).

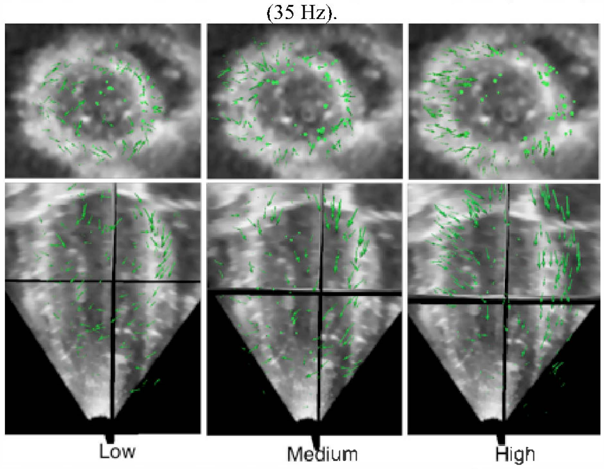

Figure 3. Cumulative ED to ES displacement fields and RT3D images at ED for low, medium, and high frame rates.

Measured Mean Displacements: The mean displacement components at ES, derived from the speckle tracking performed at the different temporal resolutions are reported in Fig. 4. We clearly observe the direct correlation between the average amplitude of the displacements and the FR, and a greater sensitivity of radial motion components to the FR (and its associated spatial resolution).

C. Strain Measurement

We illustrate in Fig. 5, strain temporal profiles at the mid level between the base and apex for the radial, circumferential, and longitudinal components for one case. We systematically observed that at higher frame rates, our method estimated greater and more homogeneous strain values and that strain values remained under-estimated for some lateral segments, despite higher frame rate.

We also compared our 3D strain values to 2D strain values computed with the the QLab Cardiac 2D Quantification Software (Philips) used in clinical routine to analyze 2D US images. Peak strain values are reported in Table II.

TABLE II. Maximum Peak Strain of the 5 Volunteers

Vol #	*Peak Values*	*15 Hz*	*25 Hz*	*35 Hz*	*2D*
1	Err	23.36	19.97	34.84	40
	Ecc	-14.89	-12.83	-16.72	-18
	Ezz	8.80	-6.86	-9.71	-19
2	Err	19.07	34.21	51.10	30
	Ecc	-13.20	-21.35	-21.96	-20
	Ezz	-8.75	-7.73	-11.13	-18.5
3	Err	45.29	33.02	56.09	17
	Ecc	-19.82	-11.36	-34.49	-16
	Ezz	-12.91	-8.20	-12.92	-16
4	Err	47.80	40.63	81.52	35
	Ecc	-24.11	-17.53	-33.01	-16.5
	Ezz	-8.40	-11.91	-9.59	-18.5
5	Err	47.29	60.78	41.74	N/A
	Ecc	-15.68	-12.76	-13.18	-16
	Ezz	-5.19	-10.81	-11.31	-19

Err = Radial Strain, Ecc = Circumferential Strain, Ezz = Longitudinal Strain, and N/A indicates that the images are insufficient for analysis.

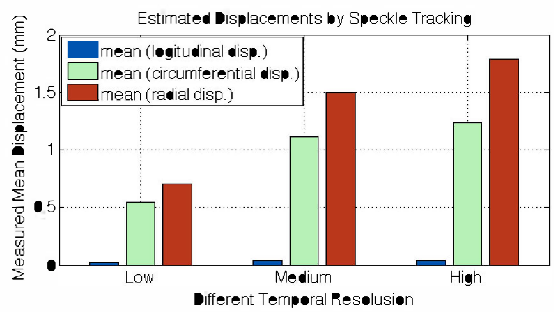

Figure 4. Mean cumulative displacements at ES estimated by speckle tracking on volunteer #2 at different frame rates: low, medium, and high.

2D and 3D strain values do not compare well directly, but we can still observe similar homogeneity in values between patients for the longitudinal strain. This component also seems to be less sensitive to FR. The circumferential and radial strains exhibited large variations in peak values (up to 9% and 33% respectively) with respect to FR, with no clear trend. We further investigated an intermediate FR of 30 Hz for five volunteers and observed high match for the amplitudes and the temporal patterns of the strain profiles compared to the higher FR, as illustrated in Fig. 6.

IV. Discussion

At high frame rates, the RT3D transducer generates more images per cardiac cycle, potentially enabling the capture of more subtle speckle motion patterns and provides more temporal intermediate samples to test point-wise template matching. On the other hand, spatial resolution is somewhat compromised and image quality is decreased, even if the pixel size of the reconstructed US images is preserved. This study revealed that using more temporal points and relying on more incremental motion decomposition (onto more frames), actually lead to larger cumulative ED to ES displacements and overall larger strain amplitudes, but not necessarily larger peak strain values.

Our point-wised speckle-tracking algorithm is tunned to drop points that it cannot track reliably. We observed that more points had to be dropped at lower frame rates. We also obtained lower cumulative displacements at lower temporal resolutions, as illustrated in Fig. 7, between ED and ES.

Further investigation needs to be performed to fully understand the correlation between strain estimate accuracy and FR in 3D. It seems that direct comparison of 2D and 3D strain measures is not possible, so that more sophisticated evaluation, comparing to tagged MRI, might be required.

In terms of clinical setting, our experimental results tend to suggest that a frame rate of 30 Hz might be sufficient for 3D speckle tracking.

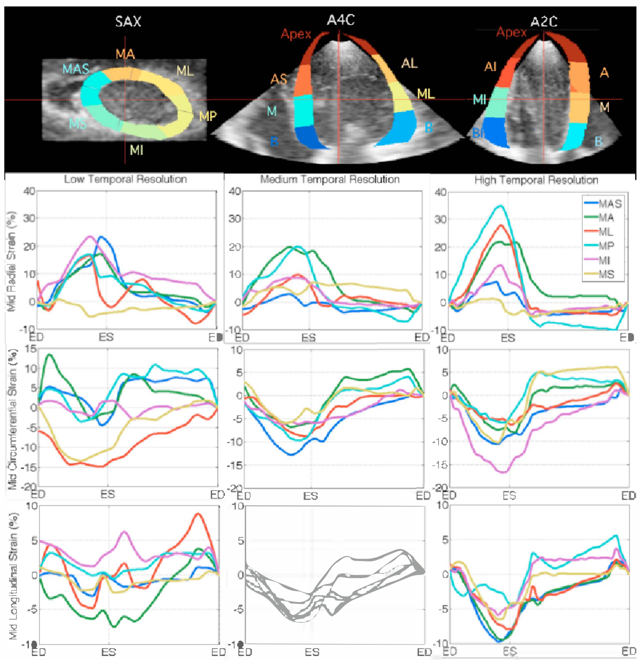

Figure 5. Strain temporal profiles for the radial (top), circumferential (middle) and longitudinal (bottom) components for 3 FR: low, medium, and high.

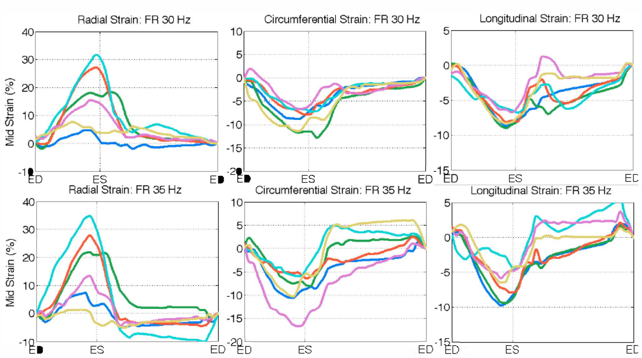

Figure 6. Strain temporal profiles computed at FR = 30 Hz (top) and at FR = 35 Hz (bottom) showing similar strain magnitude.

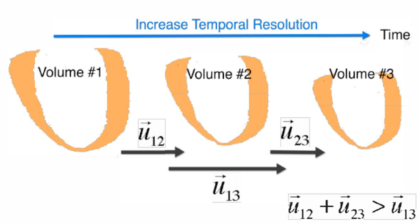

Figure 7. Illustration of the cumulated displacement estimation with different FR: $\vec{u}_{12}+\vec{u}_{23}$ estimated from frames #1, #2, and #3 (acquired at FR_1) is greater than the estimated displacement $\vec{u}_{13}$ between frames #1 and #3 (acquired at FR_2<FR_1).

ACKNOWLEDGMENT

The authors would like to thank Katy Parker for assisting in Cartesian data export, Leonid Zaurov for helpful ultrasound acquisition and Guillaume David for valuable discussion. The authors also would like to thank Enath Fhal, Nancy Lee, Sagaw Pratheepchinda, and Elie Sellam for their contributions.

REFERENCES

[1] A. M. Shah and S. D. Solomon, "Myocardial Deformation Imaging : Current Status and Future Directions," *Circ.*, vol. 125, no. 2 pp. e244-e248, 2012.

[2] V. Delgado, R. Bommel, M. Bertini, C. Borleffs, N. A. Marsan, Nucifora, N. Veire, C. Ypenburg, E. Boersma, E. R. Holman, M. J. Schalij, and J. J. Bax, "Relative Merits of Left Ventricular Dyssynchrony, Left Ventricular Lead Position, and Myocardial Scar to Predict Long-Term Survival of Ischemic Heart Failure Patients Undergoing Cardiac Resynchronization Therapy," *Circ.*, vol. 123, no. 1 pp. 70-78, 2010.

[3] Q. Duan, K. M. Parker, A. Lorsakul, E. D. Angelini, E. Hyodo, S. Homma, J. W. Holmes, and A. F. Laine, "Quantitative Validation of Optical Flow Based Myocardial Strain Measures Using Sonomicrometry," in *Proc. IEEE ISBI*, Boston Massachusattes, USA, 2009, pp. 454-457.

[4] A. Lorsakul, Q. Duan, M. J. Po, E. Angelini, S. Homma, and A. F. Laine, "Parameterization of Real-Time 3D Speckle Tracking Framework for Cardiac Strain Assessment," in *the 33rd IEEE EMBS Ann. Int. Conf.*, Boston, MA, USA 2011, pp. 2654 - 2657.

[5] J. Crosby, B. H. Amundsen, T. Hergum, E. W. Remme, S. Langeland, and H. Torp, "3-D Speckle Tracking for Assessment of Regional Left Ventricular Function," *Ultra. in Med. & Biol.*, vol. 35, no. 3 pp. 458-471, March 2009.

[6] H. Chen, T. Varghese, P. S. Rahko, and J. A. Zagzebski, "Ultrasound frame rate requirements for cardiac elastography: Experimental and in vivo results," *Ultrasonics*, vol. 49, no. 1 pp. 98-111, 2009.

[7] F. Maffessanti, H.-J. Nesser, L. Weinert, R. Steringer-Mascherbauer, J. Niel, W. Gorissen, L. Sugeng, R. M. Lang, and V. Mor-Avi, "Quantitative Evaluation of Regional Left Ventricular Function Using Three-Dimensional Speckle Tracking Echocardiography in Patients With and Without Heart Disease," *The Amer. J. Cardiol.*, vol. 104, no. 12 pp. 1755-1762, 2009.

[8] Y. Seo, T. Ishizu, Y. Enomoto, H. Sugimori, M. Yamamoto, T. Machino, R. Kawamura, and K. Aonuma, "Validation of 3-Dimensional Speckle Tracking Imaging to Quantify Regional Myocardial Deformation," *Circul.: Cardio. Img.*, vol. 2, no. pp. 451-459, 2009.

[9] Q. Duan, E. D. Angelini, and A. Laine, "Assessment of visual quality and spatial accuracy of fast anisotropic diffusion and scan conversion algorithms for real-time three-dimensional spherical ultrasound," in *SPIE Int. Symp. Med. Img.*, San Diego, CA, USA, 2004, pp. 331-342.

[10] I. Larrabide, P. Omedas, Y. Martelli, X. Planes, M. Nieber, J. A. Moya, C. B. R. Sebastián, O. Camara, M. D. Craene, B. H. Bijnens, and A. F. Frangi, "Gimias: An open source framework for efficient development of research tools and clinical prototypes," *Func Imaging and Modeling of the Heart*, vol. 5528, no. pp. 417-426, 2010.

[11] N. Toussaint, T. Mansi, H. Delingette, N. Ayache, and M. Sermesant, "An Integrated Platform for Dynamic Cardiac Simulation and Image Processing: Application to Personalised Tetralogy of Fallot Simulation," in *Proc. Eurograp. Workshop on Visual Comp. for Biomed. (VCBM)*, Delft, The Netherlands, 2008.

[12] Q. Duan, E. Angelini, S. Herz, C. Ingrassia, O. Gerard, K. Costa, J. Holmes, and A. Laine, "Dynamic cardiac information from optical flow using four-dimensional ultrasound," in *IEEE Eng. in Med. & Biol. Soc. (EMBS)*, Shangai, China, 2005, pp. 4465 - 4468.

[13] M. Cerqueira, N. Weissman, V. Dilsizian, A. Jacobs, S. Kaul, W. Laskey, D. Pennell, J. Rumberger, T. Ryan, and M. Verani, "Standardized myocardial segmentation and nomenclature for tomographic imaging of the heart," *Circul.*, vol. 105, no. pp. 539-542, 2002.