Tracking of LV Endocardial Surface on Real-Time Three-Dimensional Ultrasound with Optical Flow

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1. INTRODUCTION

- Real-time three-dimensional (RT3D) ultrasound with matrix-phased array transducers [1] enable fast, non-invasive visualization of cardiac ventricles.
- Segmentation of ventricular volumes on RT3D ultrasound is typically performed at end-diastole (ED) and end-systole (ES). Automation of the segmentation process and propagation of segmentation in time is challenging.
- In this context, a correlation-based 3D+T time optical flow algorithm was applied for tracking of myocardial surfaces.
- Initialization was performed with either manual tracing or QLAB® software (Philips Medical Systems).

2. METHODOLOGY

2.1 Correlation-Based Optical Flow

- A region-based optical flow method using correlation measures [2] was applied to RT3D ultrasound data. Correlation measures are robust to noisy conditions and can adapt to fast motion.
- A displacement vector for two consecutive time frames was computed via maximization of the cross-correlation coefficient:

$$r = \frac{\sum_{\mathbf{x} \in \Omega} (I(\mathbf{x}, t) \cdot I(\mathbf{x} + \Delta\mathbf{x}, t + \Delta t))}{\sqrt{\sum_{\mathbf{x} \in \Omega} I^2(\mathbf{x}, t)} \sqrt{\sum_{\mathbf{x} \in \Omega} I^2(\mathbf{x} + \Delta\mathbf{x}, t + \Delta t)}}$$

- Two threshold parameters were introduced:
 - A variance threshold to limit the “aperture problem”.
 - An average threshold to limit the tracking to the myocardium (“bright” regions).
- Regularization of the displacement field was performed via local averaging on a 6-connected neighborhood.

2.2 Real-Time Three-Dimensional Ultrasound Data Sets

- Tracking of the myocardial surfaces was tested on 3 data sets acquired with a SONOS 7500 3D ultrasound machine (Philips Medical Systems, Best, The Netherlands):
 - Two data sets on an **anesthetized open chest dog** before (baseline) and 2 minutes after induction of ischemia via occlusion of the proximal left anterior descending (LAD) coronary artery.
 - One transthoracic clinical data set from a **heart-transplanted patient**.

- Data acquisition was triggered with EKG and initialized at ED.
- Data set sizes: [176 160 144] with 16 frames for 1 cardiac cycle (dog-baseline), [176 160 144] with 16 frames for 1 cardiac cycle (dog-post ischemia), [224 208 204] with 16 frames for 1 cardiac cycle (patient).

Dog

Clinical

2.3 Segmentation

- Manual Tracing:** An expert performed manual tracing of all time frames in the data sets, on rotating B-scan views and translating C-scan views.
- QLAB® Segmentation:** The QLAB® software (Philips Medical Systems) was used to segment the endocardial surface. Initialization was performed by a human expert and a parametric deformable model was fit to the data at each time frame. Segmented surfaces were reviewed by expert and manually adjusted for final correction.

2. METHODOLOGY (cont.)

2.4 Surface Tracking with Optical Flow

- All data sets were pre-smoothed with anisotropic diffusion.
- An initial set of endocardial surface points was defined (from manual tracing for dog & clinical data; also from QLAB® for the clinical data).
- Optical flow (OF) algorithm was used to track the surface in time through the **whole cardiac cycle**.

2.5 Quantitative Comparison of Surfaces

- Surface reconstruction is based on finite element model (FEM) [3].
- Tracked surfaces were registered with anatomical landmarks and fitted into 64-element meshes in prolate spheroidal coordinates (λ, θ, ϕ) with bicubic Hermite interpolation [4].
- Quantitative measurements:
 - Root mean squared errors (RMSE) of the difference of the radial coordinates λ at node points for OF and manual tracing surfaces.
 - Ventricular volumes.
 - Relative errors were used to generate local relative error maps plotted as Hammer maps.

3. RESULTS

3.1 Open-Chest Dog Data

Hammer maps

OF vs. manual tracing at baseline

OF vs. manual tracing at post ischemia

3.2 Clinical Data

- Experiments: Forward and backward tracking and re-initialization using manual tracing and QLAB® segmentation.

RMSE & Volume

Manual: 0.09 (frame 09)
QLAB®: 0.08 (frame 10)
(λ = 0.6 ± 0.3 at ED, λ = 0.5 ± 0.2 at ES)

Hammer maps

OF vs. manual tracing

OF vs. QLAB® segmentation

4. DYNAMIC CARDIAC INFORMATION

4.1 Epicardium Tracking Result

- Epicardium OF tracking initialized with manual tracing was tested on the clinical data.
- Error measurements were much lower than for the endocardial surface.
- At ES, a Hammer map error analysis showed that 97% of the epicardial surface tracked with OF resulted in less than 10% differences from the manually traced surface.

4.2 Myocardium Motion Field and Dynamic Cardiac Information

- Computation of a displacement vector field between ED and ES on the endocardial and epicardial surfaces by OF tracking.
- Interpolation of myocardial motion with radial basis functions.
- Extraction of dynamic cardiac information [5]: radial displacement, thickening and twist.

One Slice

3D Rendering

5. COMPUTATIONAL TIME

	Single frame (minutes)	Total time for ejection phase (minutes)	Total time for full cycle (minutes)	Human Involvement (minutes)
Human Expert	10	70	160	160
Optical Flow	1	16	25	10

Testing Environment: “C” code on a 2.4GHz AMD 64-bit server, running Redhat Linux

6. SUMMARY & CONCLUSIONS

- A correlation-based optical flow (OF) method was evaluated on RT3D ultrasound for tracking of the LV endocardial surface defined at ED via manual tracing or segmentation with the QLAB® software from Philips Medical System.
- Quantitative evaluation showed promising ability of OF tracking to follow the endocardial surface on open-chest and clinical data sets.
- Combined with epicardium tracking and radial basis function interpolation, dense-field myocardial motion was recovered, and analyzed for dynamic cardiac information.
- This study provided encouraging results regarding OF performance to accurately track LV surfaces, yield dynamic information from RT3D ultrasound, and provide automated dynamic interpolation of segmented endocardial surfaces.
- As a semi-automated method, OF based surface tracking can minimize tedious human intervention for ventricular motion analysis.

REFERENCES

- [1] O. T. von Ramm, et al., “Real Time Volumetric Ultrasound Imaging Systems,” *Journal of Digital Imaging*, vol. 3, pp. 261-266, 1990.
- [2] J. L. Barron, et al., “Performance of Optical Flow Techniques,” *Int. J. of Computer Vision*, vol. 12, pp.43-77, 1994.
- [3] S. Herz, et al., “Novel Technique for Quantitative Wall Motion Analysis Using Real-Time Three-Dimensional Echocardiography,” *Proc. of ASE*, 2004.
- [4] C. M. Ingrassia, et al., “Impact of Ischemic Region Size on Regional Wall Motion,” *Proc. Of BMES*, 2003.
- [5] M. Schling, et al., “Myocardial Motion Analysis From B-Mode Echocardiograms,” *IEEE Trans. Image Processing*, vol.14, pp.525-536, 2005.

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