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In-line Automated Tracking for Ventricular Function With Magnetic Resonance Imaging

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An efficient nonrigid registration algorithm was implemented on the image reconstruction computer to enable in-line automatic tracking of features in steady-state free precession cine images. Four-dimensional left ventricle function analysis was performed with and without use of the in-line automatic tracking result. The method was tested in 30 patients referred for cardiac magnetic resonance imaging for a variety of clinical assessments. The time required for in-line tracking was 10 ± 2 s per slice using an image reconstructor with dual Advanced Micro Devices single-core Opteron 248 CPUs (2.2 GHz) and 8GB random access memory. The precision of clinical estimates of left ventricular volumes was significantly improved relative to the ground truth research estimates with automatic tracking versus without (6 ml vs. 9 ml in end-diastolic volume; 5 ml vs. 10 ml in end-systolic volume; both $p < 0.05$). In-line automatic tracking of image features shows promise for facilitating clinical analysis of ventricular function. (J Am Coll Cardiol Img 2010;3:860–6) © 2010 by the American College of Cardiology Foundation

Cardiac magnetic resonance (CMR) imaging is the most accurate and precise method for quantification of left ventricular (LV) mass and volume (1). Calculation of end-diastolic volume (EDV), end-systolic volume (ESV), ejection fraction (EF), stroke volume, and LV mass requires segmentation and tracking of the inner and outer contours of the LV, which is typically performed manually for each contour in a time-consuming and subjective process. Although semiautomated software can assist this process (2), analysis of the many hundreds of images per case represents a significant bottleneck.

Automatic tracking using nonrigid image registration enables tracking of image features from frame to frame by warping images between frames. We have previously shown that off-line automatic tracking using nonrigid registration can provide fast and accurate tracking of endocardial and epicardial contours throughout the cardiac cycle, using a 2-dimensional LV analysis protocol (3).

For these methods to be applied in a clinical environment, an efficient workflow must be achieved by completing the automatic image feature tracking "in-line" on the CMR scanner hardware before display to the operator. Recently, there have been several studies demonstrating the feasibility of in-line processing (4). The purpose of this study was to investigate the feasibility of in-line automatic image feature tracking for the clinical evaluation of LV function. We implemented an efficient automatic nonrigid registration image tracking algorithm on the image reconstruction computer of a standard magnetic resonance imaging scanner. The standard balanced steady-state free precession (SSFP) cine acquisition pulse sequence code was modified to perform in-line auto-

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matic tracking as part of the image reconstruction process. A 4-dimensional (being 3 spatial dimensions plus time) analysis method was adapted to utilize the in-line tracking results in a clinically streamlined analysis protocol designed to maximize throughput while maintaining accuracy and reproducibility. The method was evaluated in 30 patients with cardiovascular disease by comparing results with and without automatic tracking against a research analysis protocol developed for research trial end point evaluation in a core analysis laboratory setting. Figure 1 shows an overview of the 2 analysis pathways compared. We hypothesized that in-line tracking results would facilitate better clinical evaluation of ventricular function.

Methods

Automatic image feature tracking. The image feature tracking algorithm employed was similar to that of Li et al. (3). Briefly, a nonrigid image registration tracking procedure was performed as a warping of a current image to a reference image. The optimal deformation was defined by the minimization of the sum of the squared pixel differences between the reference image and the warped current image.

The parameters of the automatic tracking method were determined by optimizing the match between automatically tracked and manually placed contours in a training set of 36 patients with vascular disease, as described previously (3).

In-Line Implementation. The method was implemented on a Siemens (Erlangen, Germany) Avanto 1.5T scanner running the VB15 software version. The image reconstruction computer had dual Advanced Micro Devices (AMD) single-core Opteron 248 processors (2.2. GHz) and 8GB memory. The nonrigid registration algorithm was used to calculate the image warps between consecutive frames of the image sequence, within a 128 × 128 pixel region of interest in the center of the field of view. The Siemens image calculation environment framework was used to implement 3 functors (image calculation environment pipelined computation components), which were inserted into the product image reconstruction functor chain at the end of the reconstruction process. These controlled 1) preparation and dispatch of image registration processes for the multithread implementation; 2) calculation of the image warps between consecutive frames; and 3) collation of results and encoding of the deformation warps into the image headers (Fig. 2). The final deformation maps between each image pair were stored in the DICOM image headers, so that they could subsequently be used for tracking analysis. The image geometric distortion correction option was turned on by default in the acquisition protocol, so that images were corrected for geometric distortions arising from gradient nonlinearities before the registration process.

Subjects. Thirty consecutive patients (ages 12 to 75 years, 19 male) were imaged using the modified balanced SSFP pulse sequence, in the course of standard clinical CMR imaging examinations performed at our facility. This study was approved by the institutional review board, and informed consent was obtained. Patients were referred for CMR imaging for a variety of indications, including viability for ischemic heart disease, assessment of cardiomyopathies, and a range of congenital cardiac lesions. Typical imaging parameters were as follows: repetition time, echo time, and flip angle: 27.1 ms, 1.27 ms, and 69°, respectively; parallel acquisition factor 2; segments 9; bandwidth 930 Hz/pixel; field of view 340 × 276.25 mm; image matrix 256 × 208; slice thickness 6 mm; retrospectively gated; 25 cardiac frames reconstructed; and a breath-hold duration of ~12 s. Six equally spaced short-axis slices were acquired spanning the LV from apex to base, together with 3 long-axis slices orthogonal to the short axis and orientated at 60° increments around the central axis of the LV.

ABBREVIATIONS AND ACRONYMS

CMR = cardiac magnetic resonance
EDV = end-diastolic volume
EF = ejection fraction
ESV = end-systolic volume
LV = left ventricular
SSFP = steady-state free precession

Research analysis protocol. The LV mass and volumes were calculated at each frame in the cine sequence throughout the cardiac cycle using a research analysis protocol, according to the detailed standard operating procedures of our core laboratory, which were developed for the evaluation of research trial end points involving cardiac mass and volume (5). Guide-point modeling (2) was used to adaptively optimize a time-varying 3-dimensional finite element model of the left ventricle to fit each subject's images using custom software (CIM version 6.0). The model was interactively fitted to "guide points" provided by the analyst, as well as computer-generated data points calculated from the image using an edge detection algorithm (Fig. 3), by least-squares