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Analysis of Cardiac Function from MR Images

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Each year more than 1.5 million people in the United States have a heart attack. About a third of these people die. Despite a dramatic reduction in the death rate from cardiovascular disease over the past 30 years, it remains the leading cause of death for both men and women in the US, accounting for approximately 22 percent of all deaths. The economic implications of this disease are also staggering; health care economists have estimated the cost of diagnosis and treatment of heart disease at more than \$60 billion annually. This mortality rate and cost can certainly be reduced through preventative measures (diet, exercise, not smoking) and also through the development of techniques for more efficient screening and management of cardiac patients.

An exam performed in an MR scanner might replace the current sequence of tests for coronary disease, reducing costs and providing previously unavailable information on myocardial function.

Heart attacks are caused by a deficiency in *myocardial perfusion*, or blood flow to heart muscle tissue, due to a *stenosis*, or obstruction in a coronary artery. In a healthy resting human, blood is delivered to the heart muscle tissue at a rate of approximately 1 cc per gram of tissue every minute; during exercise this flow may increase five-fold. A coronary artery stenosis reduces the capacity to increase blood flow to the heart. If severe enough, the condition might cause regions of heart muscle to become *ischemic*, or oxygenstarved, resulting in electrocardiogram (ECG) irregularities and/or chest pain during exercise. In a more catastrophic scenario, an arterial blockage might completely shut off blood flow to a region of heart muscle tissue, leading to a major heart attack.

Diagnostic imaging plays a vital role in the initial screening and subsequent management of coronary disease patients. For example, a patient might complain of shortness of breath and chest pain, indicating possible coronary artery disease. To assess the severity and treatability of the patient's condition, the cardiologist might perform a series of diagnostic tests of increasing specificity, invasiveness, and cost, as deemed necessary.

First, the cardiologist would obtain an ECG while the patient's heart is stressed with physical exercise or inotropic drugs, which increase the heart rate. If the results prove suspicious, the next step is echocardiography (ultrasonic imaging) in both resting and stressed states. Unfortunately, this inexpensive bedside test is often compromised by poor image quality and can provide only a limited number of views of the heart. To get a picture of blood supply to the heart muscle tissue, the cardiologist might order a nuclear medicine *thallium scan*, in which a radionuclide is injected into the patient's blood stream during exercise, and obtain *tomograms*, or images computed from multiple projections, showing the uptake of the

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For more information

We have provided a Web page that uses MPEG to display some of the animations described in this article. To view these animations, as well as some other work from our group, run a Web browser and attach to <http://www.mri.jhu.edu/>.

radionuclide into the heart tissue. A region of poor flow will show up as a “cold spot” on the images.

The thallium scan is currently the gold standard for diagnosing myocardial ischemia. However, the test yields images of poor spatial resolution, possibly corrupted by false cold spots as a result of overlying structures, and the equipment is expensive, making for high exam costs.

Finally, X-ray coronary angiography is the procedure most prevalently used in the “cath lab” to determine the location and severity of arterial stenosis. The cardiologist advances a catheter up the aorta into the coronary vessels, guided by an X-ray monitor and periodic injections of radio-opaque dye to darken the *lumen*, or cavity of the vessel. Coronary stenosis appears as a narrowing or blockage of the vessel lumen in the X-ray images. The procedure usually produces images of excellent quality, but is invasive, not without risk, and requires expensive equipment, facility, and staff.

Recent research and development in cardiac magnetic resonance imaging (MRI) has shown that a single exam, performed entirely in an MR scanner, might well replace the sequence of tests described above. Though an MR scanner is expensive, the ability to consolidate diagnostic tests into a single session would significantly reduce costs and increase convenience for the patient. MRI might also provide the physician with diagnostic information not available from the standard battery of tests. In this article, we concentrate on one aspect of a cardiac MRI exam that provides previously unavailable information: assessment of myocardial contraction.

Myocardial wall motion

The motion of the heart muscle serves as an excellent indicator of coronary stenosis. Low blood flow to a region of myocardium often causes a reduction in contractile function, resulting in abnormal motion of the heart wall during contraction. This response can be very localized; a small section of the heart muscle that is experiencing reduced blood flow might stop participating in the contraction while the rest of the heart continues to contract normally. This wall motion abnormality actually precedes both ECG abnormalities and chest pain as an indicator of myocardial ischemia.

To measure heart wall motion, you would need to somehow place markers in the heart muscle tissue and track those markers during *systole*, or heart contraction. Until recently, physicians could not quantitatively measure heart wall motion in humans because they had no way to place temporary markers in the myocardium noninvasively. This situation changed in the late 1980's with the advent of “MR tagging.”^{1,2} In this technique, performed noninvasively within an MR scanner, planes of myocardial tissue are marked or “tagged” using radiofrequency pulses and appear as dark lines in the images. (Note that the tags are actually planes orthogonal to the imaging plane. Dark lines occur where these tagging planes intersect with the imaging plane.) The tags move with the underlying tissue and can be tracked over the heart cycle using a *cine*, or temporal sequence of images, that are *gated*, or acquired synchronously with the patient's ECG.

Figure 1 shows an example of a standard pair of cardiac MR images (top row) compared with the same images obtained after MR tagging (bottom row). Notice the added information showing the internal deformation of the contracting heart wall contained in the tagged images. MR tags such as these fade away in about half a second, so must be generated at the onset of each contraction.

This MR tagging method provides good spatial resolution, allowing measurement of displacements as small as 0.1 mm. We are developing an analysis and visualization environment for assessment of cardiac function using data obtained from MR tagged images.

We have made the most progress in the analysis of left ventricular (LV) myocardial contraction, as described here.

Imaging heart motion with MR tagging

The left ventricle of the heart pumps oxygenated blood to the rest of the body and maintains stable blood pressure in the arterial vasculature. To perform this function effectively, the heart must generate adequate force during every heartbeat. Accordingly, the LV walls are thick with striated muscle tissue.

Muscle tissue contraction or relaxation produces a *material deformation*, or change in shape, quantifiable by measuring strain over small regions. A strain estimate at a point in space and time is given by a *strain tensor*, a 3×3 matrix whose elements indicate material deformations such as stretch (or compression, a negative stretch) and shear.³ Since cylindrical coordinates are well suited to represent the shape of the LV (see Figure 2), we use a cylindrical strain tensor whose principal directions are radial, circumferential, and longitudinal.

Strain is a measure of local changes in shape and therefore not affected by global translation (constant displacement over space). Hence, translation of the heart through space during the cardiac cycle has no effect on the strain values. Global translation may be a problem with other motion analysis methods that use displacement information directly.

During the contracting phase of the cardiac cycle, properly functioning myocardium exhibits expected strain behavior: the muscle wall becomes thicker (stretches) in the radial direction and shortens (compresses) in the circumferential direction.⁴ Other stretches and shears occur, but we will concentrate on these two major components of the circumferential strain tensor. Also of interest are the eigenvectors and eigenvalues of the strain tensor. The eigenvectors give the directions of maximal stretching and maximal shortening, and the eigenvalues give the associated amounts. These eigenvectors normally line up approximately in the radial and circumferential directions, respectively.

As described above, tagged tissues appear dark in MR images, as illustrated by the straight, parallel lines in the end-diastole images of Figure 3. Tissue motion occurring after tagging distorts the tag pattern, as shown in the images acquired during contraction. Tracking the tags allows reconstruction of the underlying tissue motion and estimation of the strain in the myocardium. This method lets us quantitatively analyze myocardial function in a completely noninvasive fashion.

We obtained the images in Figure 3 using an MR image acquisition method optimized for speed, while maintaining high resolution across the tag lines.⁵ These improvements have made it possible to acquire a single-slice movie sequence (a *cine loop*) of myocardial motion in a single patient breath-hold.

We now perform MRI tagging studies routinely on both healthy volunteers and cardiac patients, with highly reproducible image quality. Figure 3 shows the basic components of a 3D tagged data set: two sets of short-axis images with orthogonal tag orientations, and one set of long-axis images with tags placed parallel to the short-axis imaging planes. These images provide displacement information in three orthogonal directions, allowing estimation of 3D displacement and strain values in the entire LV myocardium for each time frame acquired.⁶⁻⁹

Analysis

In the clinical setting, analysis of medical images from modalities such as MRI, ultrasound, X-ray, or CT is usually done by examining the raw image data in some form. The images are viewed singly, in groups, in movie sequences, or as volume renderings. We use MR techniques to encode functional information into the images. This information is often too subtle to be adequately assessed by simply viewing the raw image data. Using image segmentation and numerical computation, we can quantify functional parameters (such as wall thickening) indicative of normal heart contraction. Combining the functional parameters with the raw image data in a 3D display gives them anatomical context.

Image visualization

An MRI study of myocardial function requires the acquisition of many images for a complete picture of the contracting heart. For example, a tagging study can contain more than 300 images. We employ several methods for visualizing the raw image data. A movie display allows interactive adjustment of the slice number without pausing the movie (Figure 4). On a computer supporting 3D texture mapping (we use Silicon Graphics models), the program lets the user interactively slide the display plane between image planes, performing rapid bilinear interpolation while the movie plays. This gives the feeling of moving smoothly through the beating heart to compare apparent motion or function at different cross sections.

Images acquired on nonparallel planes can be displayed together using 3D display of 2D texture maps. Figure 5 shows short-axis and long-axis images displayed together, illustrating the relative positions of the planes on which the images were acquired in the scanner. Some innovative uses for 3D texture mapping in cardiac imaging have been developed by one of our collaborators.¹⁰

Image segmentation

The first step toward computer analysis of the image data is segmenting the images' interesting features. We have developed a semi-automatic method of extracting the inner and outer contours of the LV myocardium as well as the positions of the tags in the myocardium.¹¹ For these tasks, we use a custom-designed variant of active contours (often referred to as *snakes*).¹² An active contour's shape changes in an iterative manner to minimize one or more energy terms. Energy terms in this algorithm promote contour smoothness and pull the contours toward certain image features (for example, edges indicated by image intensity gradients). An additional energy term lets the user interactively modify the contour shape by dragging the mouse along the contour (see Figure 6).

Active contours suit interactive shape editing well, since they are computed rapidly and allow great flexibility in defining energy terms. As an added benefit, the tendency of the contour to “stick” to edges reduces variability in contour position caused by human subjectivity or error.¹³

Our implementation requires users to define a circular region of interest (ROI) for each image. Since they can often use the same ROI in all the time frames of a given slice, this step does not take much time. Users must also correctly set other controls specifying the tagging pattern before running the segmentation algorithm. Segmentation performed interactively can take 20 to 30 minutes, depending on the number of images and the image quality.

The myocardial contours define an ROI within which the computer searches for tags. Prior knowledge of the tag pattern guides the search for individual tag lines. The program marks points along the center of each tag line using a least-squares fit to a template derived from simulation. The template has the expected shape of the profile perpendicular to the tag line.¹¹

For bookkeeping purposes, the program assigns each tag line a *tag index*, as shown in Figure 7. The tag indices must match those of the corresponding tags in all slices and time frames. To check and correct these indices, we provide a wireframe display (see Figure 8) that draws the contours and tags as depth-cued, connected line segments. In this display, tags having a selected index are highlighted, making it easy to find errors in index assignment. The user can then increment or decrement the tag indices for a particular image to correct the alignment.

The user controls rotation, translation, and zoom interactively, as well as the optional display of raw image data. On a machine restricted to 2D texture mapping, the user may select an image to display with the wire-frame. On a machine with 3D texture mapping, the user may interactively “push” the image display plane smoothly through the image data. Figure 8 shows several different ways to use the wireframe to view the segmentation data in 3D with anatomical context.

Evaluating LV wall function

A viewer can appreciate myocardial wall motion qualitatively by simply observing 2D or 3D movie loops of tagged images (see <http://www.mri.jhu.edu/> for examples). The propagating wave of contraction and wall thickening becomes visible with close inspection of the movie loops. The more discerning eye can detect regions where the myocardium doesn't contract or contracts significantly less than the rest of the tissue.

Numerical methods are required to resolve more subtle abnormalities and obtain quantitative estimates of function. Toward this goal, we use the segmentation algorithm described above to track the tag positions as the heart contracts. The tag displacements in the three orthogonal directions are then least-squares fit by a harmonic series in a prolate spheroidal coordinate system.⁹ This basis representation models the nearly semi-ellipsoidal shape of the LV very well.

The fit yields an analytic function describing the *displacement field*, from which 3D displacements may be estimated at any material point in the LV. The analytic form also serves as a smooth interpolation function to reduce noise in partial derivative estimates, used to derive 3D strain tensors. Myocardial tissue dysfunction causes anomalies visible in several quantities derived from the strain tensor—radial thickening, circumferential and longitudinal shortening, and principal strains and their associated eigenvectors.⁴

Visualizing LV wall function

A major goal in visualizing LV wall function is detecting myocardial ischemia. For 3D graphical display of functional parameters, we animate a model of the LV consisting of a polygonal mesh and Gouraud-shaded quadrilaterals. The vertices of the mesh represent positions of material points in the LV tracked using the tags (see Figure 9 next page).

The user can view an animation of a selected functional parameter's temporal evolution with interactive rotation, translation, and zoom. Regions of interest in the data may be chosen by specifying ranges, threshold values, and cut planes. To see differences across the LV wall, the user may specify a number of interpolated “shells” to create in the wall and display one or a range of them. The user may display several such strain movies simultaneously and synchronously (adapting to differing heart rates) or advance through movie frames manually.

These features let a user compare healthy and diseased hearts or study the same patient before and after therapy. The user may display functional data in anatomical context by embedding the raw image data and defining landmarks, icons that may be used to point out certain anatomical features. For functional parameters that are vector quantities (such as an eigenvector

of a strain tensor), the user can color code the vector magnitudes in a scalar rendering, as in the top two rows of Figure 9, or display a 3D vector plot, as in the bottom row of Figure 9.

It often helps to view more than one functional parameter simultaneously in order to check for correlations between different parameters. Therefore, we have provided the ability to display a vector plot and a scalar rendering simultaneously. To add anatomical context, the user may display raw image data with the animated rendering. Figure 10 shows a merging of color-coded myocardial perfusion values, a vector plot of circumferential principal strain, and a single slice of raw image data. The user can obtain a better view of the raw image by using alpha blending to impart translucency to the Gouraud-shaded functional data.

Discussion

Visualizing functional cardiac data presents a significant challenge. Analyzing LV wall motion requires tracking the 3D trajectories of many material points in the myocardium through the heart cycle. Each material point is described by a large vector of functional information, such as components of the strain tensor, eigenvalues and eigenvectors of the strain tensor, displacements, perfusion, and temporal derivatives of these parameters. We have written software to create an interactive beating heart model upon which these parameters can be displayed.

Ongoing efforts in our group focus on reducing operator interaction and analysis time. We are making great strides and expect to converge on a method that can produce diagnostic information in less than one hour. We are also making progress in developing diagnostic visualization tools for MR angiography and perfusion imaging. Our work yields continual improvements in image acquisition, new experiments to obtain more detailed information about the tissue viability, development of faster analysis tools, and new ways to visualize the functional data.

These analysis techniques, when combined in an integrated package, will provide more diagnostic information at less cost than existing cardiac diagnosis methods. Risk is also reduced, since these methods are noninvasive. With these efforts and others, we expect to develop a comprehensive cardiac examination performed entirely with noninvasive MR imaging.

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Biographies

Michael Guttman is an instructor in the Department of Radiology at Johns Hopkins University School of Medicine. He received his BS in electrical engineering in 1985 and MS in biomedical engineering in 1991, both from Johns Hopkins University. Between degrees, he worked as an engineer in the medical device industry in northern California. His interests include

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Elias Zerhouni is director of the Department of Radiology at Johns Hopkins University School of Medicine. He is an international authority on thoracic imaging with MRI and CT, and has editorial affiliations with several journals. His research interests focus on the development of MR imaging methods to characterize and quantify myocardial deformation in health and disease, specifically 3D myocardial tagging.

Elliot McVeigh is director of the Biomedical Imaging Training Program at Johns Hopkins University School of Medicine. He joined the faculty in 1988. He received a BS in physics in 1984 and a PhD in medical biophysics in 1988, both from the University of Toronto. His research focus is magnetic resonance imaging and image analysis, particularly their applications to the cardiovascular system.

References

1. Zerhouni E, et al. Human Heart: Tagging with MR Imaging—A Method for Noninvasive Assessment of Myocardial Motion. *Radiology* 1988;169(1):59–63. [PubMed: 3420283]
2. Axel L, Dougherty L. MR Imaging of Motion with Spatial Modulation of Magnetization. *Radiology* June;1989 171(3):841. [PubMed: 2717762]
3. Lai, WM.; Rubin, D.; Kreml, E. *Introduction to Continuum Mechanics*. 3rd Ed.. Pergamon Press; Tarrytown, N.Y.: 1993.
4. Lugo-Olivieri, CH., et al. 2nd Proc. SMR. 3. Society of Magnetic Resonance (SMR); Berkeley, Calif.: Aug.. 1994 Temporal Evolution of Three-Dimensional Deformation in the Ischemic Human Left Ventricle: Assessment by MR Tagging; p. 1482
5. McVeigh ER, Atalar E. Cardiac Tagging with Breath-Hold Cine MRI. *Magnetic Resonance Medicine* Dec.;1992 28(2):318–327.
6. McVeigh ER, Zerhouni EA. Noninvasive Measurement of Transmural Gradients in Myocardial Strain with Magnetic Resonance Imaging. *Radiology* Sept.;1991 180(3):677–683. [PubMed: 1871278]
7. Moore CC, et al. Calculation of Three-Dimensional Left Ventricular Strains from Biplanar Tagged MR Images. *J. Magnetic Resonance Imaging* Mar./Apr.;1992 2(2):165–175.
8. Young A, Axel L. Three-Dimensional Motion and Deformation of the Heart Wall: Estimation with Spatial Modulation of Magnetization—A Model-Based Approach. *Radiology* Oct.;1992 185(1):241–247. [PubMed: 1523316]
9. O'Dell WG, et al. Three-Dimensional Myocardial Deformations: Calculations with Displacement Field Fitting to Tagged MR Images. *Radiology* June;1995 195(3):829–835. [PubMed: 7754016]

10. Solaiyappan, M., et al. Interactive Visualization for Rapid Noninvasive Cardiac Assessment. In: Rhodes, ML.; Robertson, DD., editors. *Computer*, special issue on Computer Applications in Surgery and Theraputic Procedures. 29. Jan.. 1996 p. 55-62.
11. Guttman MA, Prince JL, McVeigh ER. Tag and Contour Detection in Tagged MR Images of the Left Ventricle. *IEEE Trans. Med. Imaging* Mar.;1994 13(1):74–88. [PubMed: 18218485]
12. Kass M, Witkin A, Terzopoulos D. Snakes: Active Contour Models. *Int'l J. Comp. Vision* 1987;1(4): 321–331.
13. Bazille A, et al. Impact of Semi-Automated Versus Manual Image Segmentation Errors on Myocardial Strain Calculation by Magnetic Resonance Tagging. *Investigative Radiology* Apr.;1994 29(4):427–433. [PubMed: 8034448]

1. A comparison of standard cardiac MR images (top row) with tagged MR images (bottom row) in the same heart. The images on the left are at end-diastole, which is the phase of the heart cycle in which the ventricular cavity has achieved maximum filling. The images on the right are at end-systole, the phase of the heart cycle when the maximum amount of blood has been ejected and the muscle is at maximum contraction.

2. Short-axis and long-axis image geometry. Colored lines indicate radial, circumferential, and longitudinal directions. Short-axis image planes are perpendicular to long-axis image planes.

3.

Images from a typical cine MR cardiac tagging study. Each row contains three time frames of one slice with parallel line tags orthogonal to those in the other rows. Tags were created at end-diastole. Left column: images acquired immediately after the tags were created (end-diastole). Middle column: images acquired during contraction (systole). Right column: images acquired at the end of contraction (endsystole).

4. Images from an MR tagging study sorted by slice and time frame number. The user can jump between slices without pausing the movie. Interactive control allows smooth interpolation between slices.

5. A 3D display of images. Images on nonparallel planes are displayed together in 3D using 2D texture mapping. (a) Wireframe outlines show the image orientations relative to each other. (b) A short-axis and a long-axis image displayed together.

6. Interactive adjustment of a computer-generated contour. (a) The user presses the mouse button to pull the nearest part of the contour toward the cursor. (b) An active smoothing filter is applied while edits are made to “attract” the contour toward image edge features and keep the contour smooth. The result is an easy-to-use editing tool that reduces inter-user variability.

7. Automatically detected tag lines. The tag lines (and contours) are plotted on the tagged image. Each tag line is assigned a numerical index. (a) The first time frame at end-diastole (47 ms). (b) A time frame during systole (117 ms).

8.

Wireframe display of contours and tag lines showing different views of image and contour/tag data. (a) Basal short-axis image shown with short-axis contours and tags in the same time frame. Tags having a selected index are highlighted. (b) Long-axis image shown with short-axis contours and tags in the same time frame. The epicardial contour is highlighted. (c) Same short-axis image as shown in (a) with long-axis contours and tags in the same time frame. (d) Same short-axis image as shown in (a) with short-axis contours and tags from the same slice.

9.

A 3D display of strain in an ischemic human heart. The region exhibiting below-normal contraction is clearly indicated in the color-coded rendering.

10.

Simultaneously displayed strain, perfusion, and raw image data. The top row shows an overview of rendering. Raw image data is displayed with color-coded (nondynamic) perfusion data and vectors indicating shortening in the wall's circumference. The middle and bottom rows show details of the same slice with vertical and horizontal tags, respectively. In the abnormal region, blue indicates subnormal perfusion compared to normal regions, colored red to yellow. The black line vectors indicate circumferential shortening by their growth over time in the normal region (at 12:00), whereas little activity occurs in the diseased region (between 8:00 and 9:00). Compare the tag pattern distortion in the normal and abnormal regions.