Measurement of Cardiac Deformations from MRI: Physical and Mathematical Models

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Measurement of Cardiac Deformations from MRI: Physical and Mathematical Models

Edited by

Amir A. Amini

Washington University St. Louis, U.S.A.

and

Jerry L. Prince

Johns Hopkins University, Baltimore, U.S.A.

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Contributors

Amir A. Amini
CVIA Laboratory, Box 8086,
660 S. Euclid Ave., Washington
University School of Medicine,
St. Louis, MO 63110

Kevin F. Augenstein
Department of Engineering
Science, School of Engineering,
University of Auckland,
New Zealand

Leon Axel
Department of Radiology,
University of Pennsylvania,
Philadelphia, PA

Yasheng Chen
CVIA Laboratory, Box 8086,
660 S. Euclid Ave., Washington
University School of Medicine,
St. Louis, MO 63110

Thomas S. Denney Jr.
Department of Electrical and
Computer Engineering, Auburn
University, Auburn, AL

James S. Duncan
Department of Diagnostic
Radiology, Department of
Electrical Engineering, Yale
University School of Medicine,
New Haven, CT 06520-8042

Idith Haber
Cardiovascular Research Division,
Children's Hospital and Harvard
Medical School, Boston, MA

Jürgen Hennig
Uniklinik Freiburg, Abt.
Rontgendiagnostik, Sect. of
Medical Physics, Hugstetter Str.
55, D 79106 Freiburg, Germany

Michael Markl
Uniklinik Freiburg, Abt.
Rontgendiagnostik, Sect. of
Medical Physics, Hugstetter Str.
55, D 79106 Freiburg, Germany

Andrew D. McCulloch
Department of Bioengineering and
The Whitaker Institute of
Biomedical Engineering,
University of California San Diego,
9500 Gilman Drive, La Jolla,
CA 92093-0412, USA

Elliot R. McVeigh
Laboratory of Cardiac Energetics,
NHLBI, Building 10, Room
B1D416, Bethesda,
MD 20892-1061

Dimitris Metaxas
Department of Computer and
Information Science, University of
Pennsylvania, Philadelphia, PA

Nael F. Osman
Department of Radiology, Johns
Hopkins University, 3400 N.
Charles St., Baltimore, MD 21218

Cengizhan Ozturk
Bogazici University, Institute of
Biomedical Engineering,
80815 Bebek, Istanbul, Turkey

Xenophon Papademetris
Department of Diagnostic
Radiology, Yale University School
of Medicine, New Haven,
CT 06520-8042

Norbert J. Pelc
Department of Radiology
Stanford University, Palo Alto, CA

Jerry L. Prince
Electrical and Computer
Engineering, Johns Hopkins
University, 3400 N. Charles St.,
Baltimore, MD 21218

Nathaniel Reichek
Research and Education
Foundation, DeMatteis Center,
St. Francis Hospital,
100 Port Washington Blvd.,
Roslyn, NY 11576

Britta Schneider
Uniklinik Freiburg, Abt.
Rontgendiagnostik, Sect. of
Medical Physics, Hugstetter Str.
55, D 79106 Freiburg, Germany

Albert J. Sinusas
Section of Cardiovascular
Medicine, Department of Internal
Medicine, Yale University School
of Medicine, New Haven,
CT 06520-8042

Alistair A. Young
Department of Anatomy with
Radiology, School of Medicine,
University of Auckland,
New Zealand

Yu-Ping Wang
The Advanced Digital Imaging
Research, LLC.,
2525 South Shore Blvd., #100,
League City, TX 77573

Yudong Zhu
GE Corporate Research and
Development, Schenectady,
New York

Preface

This book describes the latest imaging and image analysis techniques that have been developed at leading centers for the visualization, analysis, and understanding of normal and abnormal cardiac motion with magnetic resonance imaging (MRI). The use of MRI in measuring cardiac motion is particularly important because MRI is non-invasive, and it is the only modality capable of imaging detailed intramural motion *within* the myocardium. Other imaging modalities must infer the motion of the myocardium from the motion of just the endocardium and epicardium. In addition to its novel capabilities for imaging the intramural myocardial motion in 3D, first-pass contrast perfusion imaging, delayed contrast-enhanced imaging of myocardial viability, and MR imaging of the coronary arteries are experiencing rapid progress as well, making the one-stop-shop goal of cardiovascular MRI a reality in the near future.

There have been many significant advances in the field of cardiovascular MRI over the past several years. This book brings together many of the key advances in the imaging of cardiac motion — the data acquisition, image processing, and image analysis — in one bound volume. The book is organized to provide fundamentals about the mechanical properties of the heart, acquisition technologies including MR tagging and phase-contrast, and image processing and analysis methods that are used to reveal detailed myocardial velocity, displacement, and strain patterns in the heart muscle. While primary emphasis is on the left ventricle, new emerging applications to the right ventricle and atria are presented here as well. Information about the use of cardiac MR imaging of function for the scientific purpose of understanding heart motion and for the clinical need to diagnose heart disease is also represented herein.

We have collected chapters for inclusion in this book which should serve a variety of purposes. Biomedical engineers, medical physicists, computer scientists, and physicians interested in learning about the latest advances in cardiovascular MRI should find this book to be a valuable educational resource. In particular, it is more tutorial in nature than most of the technical papers where the research was originally published. Practitioners and researchers working in the field of cardiovascular MRI will find the book to be filled with practical technical details and references to other work, enabling the implementation of existing methods and serving as a basis for further research in the area. Non-specialists may find the reading to be technically challenging, but will certainly be inspired by the successful interplay between medical and engineering challenges, a key aspect of research developments described herein.

We now give a brief overview of the chapters contained within the book.

In Chapter 1, Andrew McCulloch gives an overview of the relationship between stress and strain in the myocardium. Stress is the force per unit area which acts on surfaces between adjacent regions of the muscle, whereas strain is a measure of the resulting deformation; often reported as a percent change in length. Measurement of these quantities, especially the strain of myocardial deformation, is a recurring theme in the book. This chapter provides the foundations for understanding the importance of this concept.

In Chapter 2, Nathaniel Reichek gives an overview of clinical application of cardiac tagging. Applications of MR tagging for assessment of strain and fiber shortening in normal physiology, and the changes in left-ventricular hypertrophy, ischemic heart disease, cardiomyopathies, and pericardial constriction are discussed. Additionally, a discussion of stress-testing with MRI using inotropic stimulation is provided.

In Chapter 3, Kevin Augenstein and Alistair Young discuss their latest Finite Element Modeling (FEM) approaches to analysis of tagged MRI data of the intact left and right ventricles. Using principal component analysis (PCA) in a normal population, Augenstein and Young report on the principal statistical modes of deformation of the left-ventricle from fitted FEM models.

In Chapter 4, Idith Haber, Dimitris Metaxas, and Leon Axel describe physics-based FEM deformable models for analysis of left and right ventricles. The approach fits a biventricular FE model to tag data based on the Lagrangian equations of motion. Application of methods to tagged MRI data collected in normal and hypertrophic hearts are reported.

In Chapter 5, Cengizhan Ozturk and Elliot McVeigh, describe methods for motion analysis of the whole heart, concentrating on atrial motion. Since the atria are thin and tagged MR methods do not lend themselves to atrial motion analysis, they describe a surface-based registration method for determining atrial deformations from MRI. For left and right ventricular motion analysis, circumferential strains are reported as a function of time.

In Chapter 6, Nael Osman and Jerry Prince describe HARmonic Phase (HARP) MRI, a new method based on tagged MRI for fast assessment of myocardial kinematics. Due to the relatively little post-processing which is involved, HARP may be used in the future within a cardiac monitoring or MRI stress testing setting.

In Chapter 7, Thomas Denney Jr. describes Bayesian methods for localization of tag lines in short-axis and long-axis tagged MRI slices. For carrying out comprehensive analysis of cardiac deformations over time, tag lines need to be localized on all acquired image data. The approach automatically estimates location of tag lines on tagged MRI slices of the left-ventricle.

In Chapter 8, Yasheng Chen, Yu-Ping Wang, and Amir Amini describe B-spline methods for analysis of tagged MRI data. They develop a fast approach to reconstruction of 2D tissue deformations from tagged MR images using a shifted B-spline bases representation of the deformation field. Additionally, they use deformable B-spline surface representations for triplets of intersecting tag planes to compute and track 3D location of myocardial beads.

In Chapter 9, Michael Markl, Britta Schneider, and Jürgen Hennig discuss MRI phase velocity encoding for assessment of ventricular function. The chapter provides a thorough description of phase-contrast MRI and describes an approach to analysis of acquired velocity data which involves decomposing the myocardial motion into radial (thickening) and tangential (angular and torsional) components.

In Chapter 10, Yudong Zhu and Norbert Pelc describe a dynamic FEM-based approach called DMESH for analysis of phase-velocity data. The approach which involves fitting velocity samples over an extended region at all time frames, analytically constructs the displacement and strains from the collected velocity data.

In Chapter 11, Xenophon Papademetris, Albert Sinusas, and James Duncan use biomechanically inspired models to measure displacements and strain from Cine MRI. The approach uses expected fiber directions in normal volunteers across the myocardial wall in a Bayesian framework to interpolate initial endocardial and epicardial surface displacements. Initial surface displacements are measured by tracking curvature landmarks.

We are thankful for the help of many people during the development of this book. We would first like to thank all the contributors for spending time to write the excellent chapters that comprise this volume. The product is primarily a result of their expertise and hard work. We are also grateful for the help of two of our students, whose efforts were truly indispensable in the preparation of this book. Jordan Woerndle (Washington University in St. Louis) set up and maintained a highly professional web site for the authors' use in the development of the book and Aaron Carass (Johns Hopkins University) painstakingly solved all the LaTeX 2_ε problems, edited and re-edited all of the chapters, and compiled the final product before you. We would like to thank Paul Roos and James Finlay of Kluwer Academic Publishers, who guided us through the details of book publishing (and who tolerated numerous delays in getting the final book to press). Finally, we would also like to thank Max Viergever, Editor of the Kluwer's Computational Imaging and Vision book series. Max first suggested the idea for this book to us in the summer of 1999 and has patiently urged and guided us to its completion.

Amir A. Amini and Jerry L. Prince
Washington University in St. Louis
Johns Hopkins University