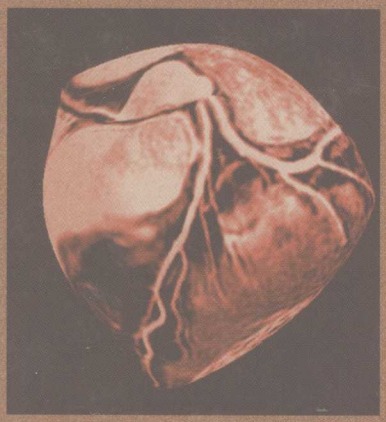
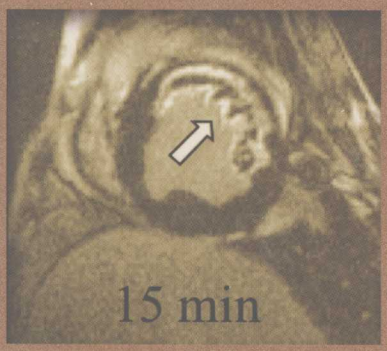
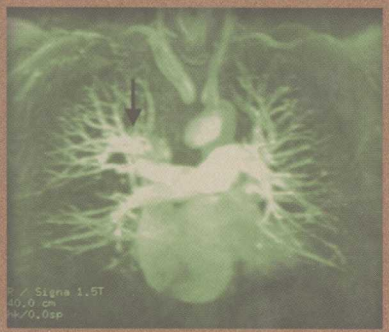
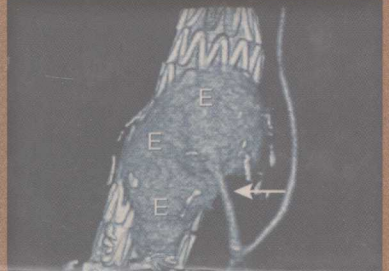
Second Edition

MRI and CT of the Cardiovascular System



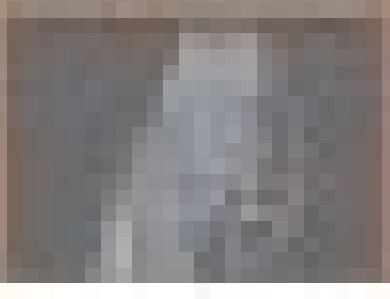






Charles B. Higgins
Albert de Roos

LIPPINCOTT WILLIAMS & WILKINS



MRI and CT of the Cardiovascular System

Carlos E. Higgins
Albert de Roos

MRI and CT of the Cardiovascular System

Second Edition

Charles B. Higgins, MD
Professor
Department of Radiology
University of California, San Francisco
San Francisco, California

Albert de Roos, MD
Professor and Vice Chairman
Department of Radiology
Leiden University Medical Center
Leiden, The Netherlands

LIPPINCOTT WILLIAMS & WILKINS
A **Wolters Kluwer** Company
Philadelphia • Baltimore • New York • London
Buenos Aires • Hong Kong • Sydney • Tokyo

Acquisitions Editor: *Lisa McAllister*
Managing Editor: *Kerry Barrett*
Marketing Manager: *Angela Panetta*
Project Manager: *Nicole Walz*
Senior Manufacturing Manager: *Ben Rivera*
Design Coordinator: *Terry Mallon*
Cover Design: *Joseph DePinho*
Production Services: *Maryland Composition Inc*
Printer: *Edwards Brothers*

530 Walnut Street
Philadelphia, Pennsylvania 19106 USA

Printed in the United States of America

Library of Congress Cataloging-in-Publication Data

MRI and CT of the cardiovascular system / [edited by] Charles B. Higgins and Albert de Roos.—2nd ed.
p. ; cm
Rev. ed. of: Cardiovascular MRI and MRA. c2003.
Includes bibliographical references and index.
ISBN 0-7817-6271-5
1. Cardiovascular system—Magnetic resonance imaging. 2. Cardiovascular system—Diseases—Diagnosis. I. Higgins, Charles B. II. Roos, Albert de, 1953- III. Cardiovascular MRI and MRA.
[DNLM: 1. Heart Diseases—diagnosis. 2. Magnetic Resonance Imaging. 3. Tomography, X-Ray Computed. 4. Vascular Diseases—diagnosis. WG 141.5.M2 M939 2006]
RC670.5.M33C375 2006
616.1′07548—dc22

2005014962

To purchase additional copies of this book, call our customer service department at (800) 639-3030 or fax orders to (301) 824-7390. International customers should call (301) 714-2324.

Visit Lippincott Williams & Wilkins on the Internet: http://www.lww.com. Lippincott Williams & Wilkins customer service representatives are available from 8:30 am to 6:30 pm, EST.

MRI and CT of the Cardiovascular System

Second Edition

Dedication

To our residents and fellows whose work has contributed to progress in cardiovascular MRI and CT

PREFACE

The first edition of this book was published at a time when MR was becoming an important imaging technique for the diagnosis of cardiovascular diseases. Since that time, CT has also been recognized as an important technology for the evaluation of the cardiovascular system. Although the first images of the beating heart using CT were produced in the late 1970s and the first images of the heart using MR around 1982, both techniques remained immature and unfamiliar for cardiovascular diagnosis for two decades or more. Technological advances in the past several years have rendered both techniques highly effective and for some applications, unique in the evaluation of the cardiovascular system. These techniques can provide precise depiction of cardiovascular morphology and quantification of physiology.

The first edition was published in 2003. This second edition appears after a relatively short interval. This approach was dictated by rapid technological advances and increased recognition of clinical applications of cardiovascular MR. Furthermore, during this interval, multi-detector CT has emerged as an important diagnostic modality, especially for the evaluation of ischemic heart disease.

Our goal in preparing this book is to provide fully updated information on the use of MR and CT for the assessment of cardiac and vascular diseases. Similar to the first edition, we recognized the rapid advance in both MR and CT technology and the constantly evolving concepts on their clinical use. Consequently, we again embarked upon a schedule for writing this book that spanned less than a year from conception to completion of the manuscript.

The authors include basic scientists, cardiologists, and radiologists from around the world. These experts have had a long involvement in fostering the development of cardiovascular MR and CT.

Charles B. Higgins, MD
Albert de Roos, MD

CONTRIBUTING AUTHORS

Charles M. Anderson, MD, PhD
Clinical Professor of Radiology
University of California, San Francisco
San Francisco, California

Evan Appelbaum, MD
Instructor in Medicine
Harvard Medical School
Department of Cardiology
Beth Israel Deaconess Medical Center
Boston, Massachusetts

Philip A. Araoz, MD
Assistant Professor of Radiology
Mayo Clinic
Rochester, Minnesota

Håkan Arheden, MD, PhD
Associate Professor and Vice Chairman of Radiology and Clinical Physiology
Lund University Hospital
Lund, Switzerland

Sonya V. Babu-Narayan, BSc, MRCP
Clinical Fellow in Adult Congenital Heart Disease and Cardiovascular Magnetic Resonance
Royal Brompton Hospital and Imperial College
London, United Kingdom

Frank M. Baer, PhD, MBA
Professor of Cardiology
MBA Public Health
Clinic for Internal Medicine
University of Köln
Köln, Germany

Jeroen J. Bax, MD
Department of Cardiology
Leiden University Medical Center
Leiden, The Netherlands

Christoph R. Becker, MD
Associate Professor
Section Chief Body CT
University Hospital Munich
Munich, Germany

Jan Bogaert, MD, PhD
Professor of Radiology
University Hospitals
Catholic University of Leuven
Leuven, Belgium

René Botnar, PhD
Cardiovascular Division
Beth Israel Deaconess Medical Center
Boston, Massachusetts

Jens Bremerich, MD, PhD
Department of Radiology
University Hospital Basel
Basel, Switzerland

Arno Bücker, MD, MSc
Associate Professor of Diagnostic Radiology
University Hospital Aachen
Aachen, Germany

Peter T. Buser, MD
Professor and Vice Chairman of Cardiology
University Hospital Basel
Basel, Switzerland

Filippo Cademartiri, MD, PhD
Department of Radiology
Erasmus Medical Center
Rotterdam, The Netherlands

Pierson Chiou, MD
Assistant Clinical Professor of Radiology
University of California, San Francisco
San Francisco, California

Albert de Roos, MD
Professor and Vice Chairman of Radiology
Leiden University Medical Center
Leiden, The Netherlands

Pim J. de Feyter, MD, PhD
Radiologist
Cardiologist, Thorax Center
Erasmus Medical Center
Rotterdam, The Netherlands

Joost Doornbos, MD
Department of Radiology
Leiden University Medical Center
Leiden, The Netherlands

Steven Dymarkowski, MD, PhD
Associate Professor in Radiology
University Hospitals K.U. Leuven
Leuven, Belgium

Michael D. Elliott, MD
Assistant Professor of Medicine
Attending Physician
Duke University Medical Center
Durham, North Carolina

Peter Ewert, MD
Assistant Professor of Pediatrics
Cardiac Catheterization Laboratory
Department of Congenital Heart Diseases
German Heart Institute Berlin
Berlin, Germany

Rossella Fattori, PhD
Professor of Radiology
Cardiovascular Unit
University Hospital Sant'Orsola
Bologna, Italy

Zahi A. Fayad, PhD
Mount Sinai School of Medicine
Mount Sinai Hospital
Imaging Science Laboratories
New York, New York

Matthias G. Friedrich, MD, FESC
Associate Professor
Director, Stephenson CMR Centre at the Libin Cardiovascular Institute
University of Calgary
Calgary, Alberta, Canada

Jacob Geleijns, PhD
Medical Physicist
Department of Radiology
Leiden University Medical Center
Leiden, The Netherlands

Thomas M. Grist, MD
John Juhl Professor and Chair of Radiology
Clinical Sciences Center
Madison, Wisconsin

Heynric B. Grotenhuis, MD
Departments of Radiology and Cardiology
Leiden University Medical Center
Leiden, The Netherlands

Thomas H. Hauser, MD
Instructor in Medicine
Cardiovascular Division
Harvard University Medical School
Beth Israel Deaconess Medical Center
Boston, Massachusetts

Marie-Christine Herregods, MD, PhD
Professor of Cardiology
University Hospitals
Catholic University of Leuven
Leuven, Belgium

Charles B. Higgins, MD
Professor of Radiology
University of California, San Francisco
San Francisco, California

Robert M. Judd, PhD
Associate Professor of Medicine and Radiology
Co-Director, Duke Cardiovascular-Magnetic Resonance Center
Duke University Medical Center
Durham, North Carolina

J. Wouter Jukema, MD
Department of Cardiology
Leiden University Medical Center
Leiden, The Netherlands

Dagmar I. Keller, MD
Division of Cardiology
University Hospital Basel
Basel, Switzerland

Philip J. Kilner, MD, PhD
Consultant and Reader in Cardiovascular Magnetic Resonance
Royal Brompton Hospital and Imperial College
London, United Kingdom

Raymond J. Kim, MD
Associate Professor of Medicine and Radiology
Co-Director, Duke Cardiovascular Magnetic-Resonance Center
Duke University Medical Center
Durham, North Carolina

Sebastian Kozerke, PhD
University of Zurich and Swiss Federal Institute of Technology (ETH)
Institute for Biomedical Engineering
Zurich, Switzerland

Dara L. Kraitchman, VMD, PhD
Associate Professor of Radiology
Russell H. Morgan Division of MRI Research
Johns Hopkins University
Baltimore, Maryland

Gabriel P. Krestin, MD, PhD
Professor and Head of Department of Radiology
University Hospital Rotterdam
Rotterdam, The Netherlands

Lucia J.M. Kroft, MD, PhD
Department of Radiology
Leiden University Medical Center
Leiden, The Netherlands

Gabriele A. Krombach, MD, PhD
Department of Diagnostic Radiology
University Hospital RWTH-Aachen
Aachen, Germany

Titus Kuehne, MD
Pediatric Cardiologist
Department of Congenital Heart Disease/Pediatric Cardiology
German Heart Institute Berlin
Berlin, Germany

Hildo J. Lamb, MD, MSc, PhD
Senior Scientist
Radiology Resident
Leiden University Medical Center
Leiden, The Netherlands

Boudewijn P.F. Lelieveldt, PhD
Assistant Professor of Radiology
Division of Image Processing
Leiden University Medical Center
Leiden, The Netherlands

Michael J. Lipinski, BS
Third Year Medical Student
Virginia Commonwealth University School of Medicine
Richmond, Virginia

Venkatesh Mani, PhD
Post Doctoral Fellow of Radiology
Mount Sinai School of Medicine
New York, New York

Warren J. Manning, MD
Professor of Medicine and Radiology
Harvard Medical School
Section Chief, Non-invasive Cardiac Imaging
Beth Israel Deaconess Medical Center
Boston, Massachusetts

Nico R. Mollet, MD
Departments of Radiology and Cardiology
Erasmus Medical Center
Rotterdam, The Netherlands

Eike Nagel, MD
Department of Cardiology
Germany Heart Institute Berlin
Berlin, Germany

Karen G. Ordovás, MD
Research Fellow in Cardiovascular Imaging
University of California, San Francisco
San Francisco, California

Jaap Ottenkamp, MD, PhD, FESC
Department of Pediatric Cardiology
Leiden University Medical Center
Leiden, The Netherlands
Emma Children's Hospital
Amsterdam, The Netherlands

Harald H. Quick, PhD
Senior Physicist
Department of Diagnostic and Interventional Radiology
Section Biomedical Imaging
University Hospital, Essen
Essen, Germany

Frank E. Rademakers, MD, PhD
Professor of Cardiology
Univeristy Hospitals Leuven
Catholic University Leuven
Leuven, Belgium

Reza Razaavi, MBBS, MD, MRCP (UK), MRCHPCH
Professor of Pediatric Cardiovascular Science
Deputy Chair
Division of Imaging Sciences
King's College
Director of Cardiac Magnetic Resonance Imaging
Guy's and St. Thomas' NHS Trust
London, United Kingdom

Gautham P. Reddy, MD, PhD
Associate Professor of Radiology
Director, Diagnostic Radiology Residency Program
Chief, Cardiac Imaging
University of California, San Francisco
San Francisco, California

Johan H.C. Reiber, PhD
Professor of Radiology
Division of Image Processing
Leiden University Medical Center
Leiden, The Netherlands

Vincenzo Russo, MD
Department of Radiology
Cardiovascular Unit
University Hospital Sant'Orsola
Bologna, Italy

Maythem Saeed, DVM, PhD
Professor of Radiology
University of California, San Francisco
San Francisco, California

Hajime Sakuma, MD
Associate Professor and Vice Chairman
Department of Diagnostic Radiology
Mie University Hospital
Tsu, Mie, Japan

Liesbeth P. Salm, MD
Department of Cardiology
Leiden University Medical Center
Leiden, The Netherlands

David A. Saloner, PhD
Professor of Radiology
University of California, San Francisco
San Francisco, California

Matthias Schmidt, Priv.-Doz, MD
Clinic and Health Center for Nuclear Medicine
University of Köln
Köln, Germany

Joanne D. Schuijf, MD
Department of Cardiology
Leiden University Medical Center
Leiden, The Netherlands

Juerg Schwitter, MD
Co-Director Cardiac MR Unit
Department of Cardiology and Internal Medicine
University Hospital Zurich
Zurich, Switzerland

Marc Sirol, MD
Assistant Professor of Cardiology
Hôpital Lariboisière
Paris, France
Cardiovascular Institute
Mount Sinai School of Medicine
New York, New York

Freddy Ståhlberg
Professor of Medical Radiation Physics
Lund University
Lund, Sweden

William Stanford, MD
Professor of Radiology
Cardiovascular and Chest Division
Lucille A. & Roy J. Carver University of Iowa College of Medicine
Iowa City, Iowa

Matthias Stuber, PhD
Associate Professor of Radiology
Russel H. Morgan Division of MRI Research
Departments of Cardiology and Electrical and Computer Engineering
Johns Hopkins University
Baltimore, Maryland

Andrew M. Taylor, BA (Hons.), BM BCh, MD, MRCP (UK), FRCR
Senior Clinical Lecturer in Cardiovascular Imaging
Institute of Child Health
Univerisity College London
Great Ormond Street Hospital for Children
London, United Kingdom

Brad H. Thompson, MD
Associate Professor of Radiology
Director of General Radiology
Roy J. and Lucille A. Carver College of Medicine
University of Iowa Hospitals and Clinics
Iowa City, Iowa

Frank J. Thornton, MD
Assistant Professor of Radiology
Clinical Sciences Center
Madison, Wisconsin

Rob J. van der Geest, MSc
Assistant Professor of Radiology
Division of Image Processing
Leiden University Medical Center
Leiden, The Netherlands

Edwin van der Linden, MD
Department of Radiology
Leiden University Medical Center
Leiden, The Netherlands

Ernst E. van der Wall, MD
Department of Cardiology
Leiden University Medical Center
Leiden, The Netherlands

Hubert W. Vliegen, MD, PhD, FESC
Department of Cardiology
Leiden University Medical Center
Leiden, The Netherlands

Martin N. Wasser, MD
Department of Radiology
Leiden University Medical Center
Leiden, The Netherlands

Ralf Wassmuth, MD
Franz-Volhard-Clinic
Helios Klinikum Berlin
Charité University Berlin
Berlin, Germany

Norbert Watzinger, MD
Associate Professor of Cardiology
Medical University Graz
Graz, Austria

Oliver Weber, PhD
Assistant Adjunct Professor of Radiology
University of California, San Francisco
San Francisco, California

François E.J.A. Willemssen, MD
Department of Radiology
Leiden University Medical Center
Leiden, The Netherlands

Susan B. Yeon, MD, JD
Assistant Professor of Medicine
Cardiovascular Division
Harvard Medical School
Beth Israel Deaconess Medical Center
Boston, Massachusetts

CONTENTS

1

Clinical Approach to Cardiovascular Magnetic Resonance Techniques

Hildo J. Lamb, Sebastian Kozerke, Joost Doornbos, Jeroen J. Bax, and Albert de Roos

Cardiovascular magnetic resonance (CVMR) techniques are changing rapidly, and CVMR is currently in an exciting and crucial phase for its final clinical acceptance. The main technical limitations are overcome by development of improved scanner hardware, software, and image processing tools. In this chapter, basic and advanced CVMR techniques will be discussed in the context of clinical application. Based on a virtual patient examination, relevant techniques will be discussed. The focus will be on techniques for functional evaluation of heart disease. Special attention is given to reduced data acquisition methods, because these techniques are causing a revolution within the field of CVMR. MR techniques for perfusion imaging, visualization of delayed enhancement, coronary artery MR angiography, and vessel wall imaging will be discussed in more detail in other chapters and will be briefly discussed here.

COILS

Clinical cardiac exams can be performed using the standard body coil, although image quality is suboptimal. The main problem is the limited in-plane spatial resolution of around 3 mm^2. High spatial resolution is especially important for accurate assessment of wall motion abnormalities due to, for example, myocardial infarction. In the past, reliable images were obtained using the body coil for assessment of global and regional myocardial wall motion (Fig. 1.1). When an imaging center is particularly interested in CVMR, using a standard surface coil is useful, such as a single circular coil with a diameter of approximately 14 cm, which improves substantially image quality and spatial resolution. The best alternative is a dedicated cardiac phased array coil constructed of multiple elements. This type of coil is now commercially available from most scanner manufacturers (Fig. 1.1). The main advantage is the further improved image qual-

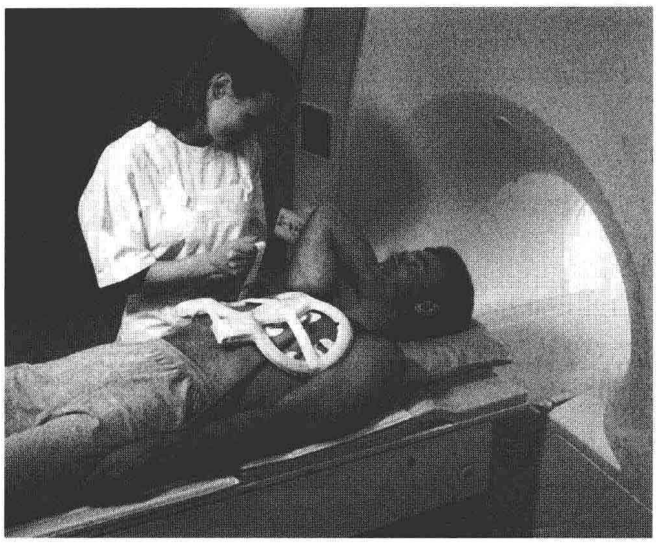


Figure 1.1. Practical setup of a dedicated cardiac phased array coil and vector ECG. The standard body coil is integrated with the magnet bore. (Courtesy of Philips Medical Systems, Best, The Netherlands.)

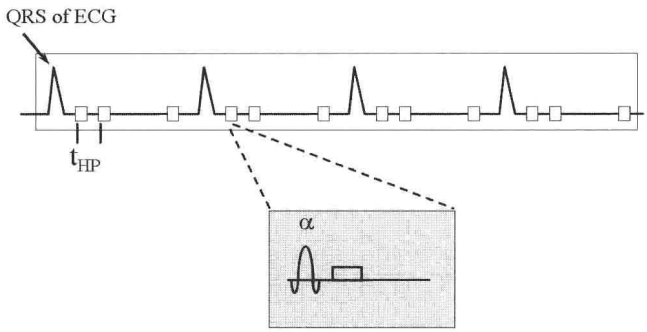


Figure 1.2. Schematic diagram of the basic principle of a gradient echo MR sequence [GRE, or fast-field echo (FFE)] in relation to the timing within the cardiac cycle. After each radio frequency (rf) excitation pulse (α), one line in k-space is acquired (gray area). In total, four heart beats are shown, resulting in an image of 4 k-lines. Suppose an image of 120 k-lines is required, the procedure needs to be repeated 30 times, leading to a total of heart beats of 120. With a heart rate of 60 beats-per-minute, the acquisition can be completed during continuous breathing within 2 minutes. White squares indicate heart phase image segments; t_{HP}, time between each heart phase (temporal resolution).

ity, spatial resolution, and the larger field of view. An additional advantage is that phased array coils allow application of the SENSE technique (1). SENSE represents a revolutionizing technology in CVMR; its principle is based on parallel imaging with use of all coil elements. Each coil has a different sensitivity profile, which can be exploited to unfold undersampled acquisitions and to reduce the density of the acquired k-space data, thus speeding up scan time (see later for details). Using SENSE, currently, a twofold increase in imaging speed can be obtained as standard; in an experimental setting higher factors were reached. In general, SENSE contributes significantly to the clinical acceptance of CVMR, because it reduces MR scan time, making it comparable to ultrasound or computed tomographic (CT) examinations.

CARDIAC MOTION COMPENSATION

Cardiac motion compensation is performed by synchronizing the image acquisition to the electrocardiogram (ECG) signal. Image formation in MR is based on filling "k-space" during data acquisition (see Appendix); this concept will not be explained further in this context, because many thorough and comprehensive publications are available on this topic (2–6). ECG-triggering is aimed at filling k-space in multiple steps, based on the timing within the cardiac cycle (Figs. 1.2 to 1.6). For example, to construct a movie of a cardiac slice, approximately 20 cardiac phases (time frames) are needed to obtain a sufficiently high temporal resolution. In general, a time resolution of less than 40 milliseconds per cardiac phase image is needed to enable selection of the end-systolic time frame, for calculation of, for example, the end-systolic volume and ejection fraction. For high resolution, clinical imaging, these 20 cardiac images per slice cannot be obtained at once. Therefore, ECG-triggering was developed, to synchronize the partial k-space filling to the cardiac cycle. Suppose we need 128 k-lines for the first cardiac phase image, but we can only acquire 12 k-lines for that image per heart beat, then 11 heart beats are needed to complete k-space filling for that image. This would take a breath-hold of approximately 11 seconds at a heart rate of 60 beats per minute. Of course, all 20 cardiac phases are acquired at once, so within 11 seconds a full movie of a cardiac slice can be obtained.

Currently, two types of ECG triggering methods are available. The first is prospective triggering, meaning that image

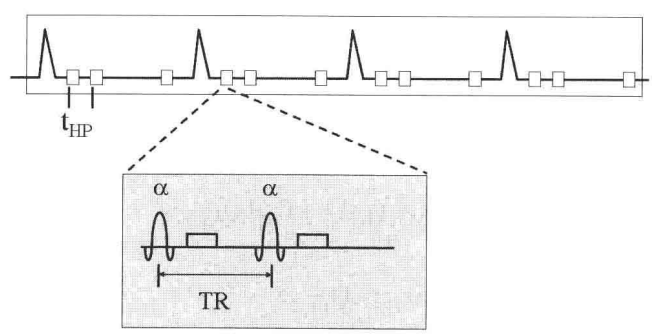


Figure 1.3. Schematic diagram of the basic principle of a turbo-field echo (TFE) MR sequence in relation to the timing within the cardiac cycle. After each rf excitation pulse (α), one line in k-space is acquired, which is repeated two times in this case (turbo-factor 2), leading to a total of two acquired k-lines per heart phase image segment per cardiac cycle (gray area). In total, four heart beats are shown, resulting in an image of 8 k-lines. Suppose an image of 120 k-lines is required, the procedure needs to be repeated 15 times, leading to a total of heart beats of 60. With a heart rate of 60 beats-per-minute, the acquisition can be completed during continuous breathing within 60 seconds. White squares indicate heart phase image segments; t_{HP}, time between each heart phase (temporal resolution); TR, repetition time between rf excitations.

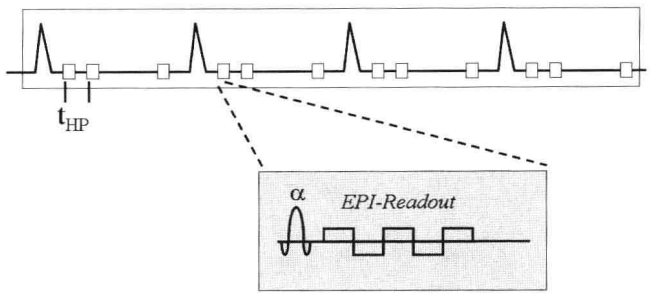


Figure 1.4. Schematic diagram of the basic principle of an echo-planar MR sequence (EPI) in relation to the timing within the cardiac cycle. After each rf excitation pulse (α), in this example five lines in k-space are acquired (EPI factor 5), leading to a total of five acquired k-lines per heart phase image segment per cardiac cycle (gray area). In total, 4 heart beats are shown, resulting in an image of 20 k-lines. Suppose an image of 120 k-lines is required, the procedure needs to be repeated six times, leading to a total of heart beats of 24. With a heart rate of 60 beats-per-minute, this can be performed during a breath-hold of 24 seconds. White squares indicate heart phase image segments; t_{HP}, time between each heart phase (temporal resolution).

acquisition starts at a fixed delay after the QRS-complex of the ECG and stops around 80% of the cardiac cycle. Consequently, the 20 cardiac phases are distributed during this 80% of time. The last 20% of the cardiac cycle is not imaged. This technique is suitable to image systolic heart function. When one is interested in the last part of the cardiac cycle to evaluate diastolic heart function, a different method can be applied. Retrospective ECG gating acquires image data irrespective of the ECG, while the ECG is recorded in parallel. Once the MR acquisition is finished, the computer calculates afterward (retrospectively) the appropriate cardiac phases, based on the stored ECG and k-space data. The last part of the cardiac cycle can also be imaged. This technique has been applied clinically, mostly in conjunction with MR flow mapping (see later), because it allows estimation of, for example, diastolic filling pattern or regurgitation volume in patients with mitral valve insufficiency. Recently, retrospective gating became available in combination with faster scan techniques, such as echo-planar imaging and balanced gradient echo acquisitions (see later), so now the standard is retrospective ECG triggering for most CVMR imaging purposes.

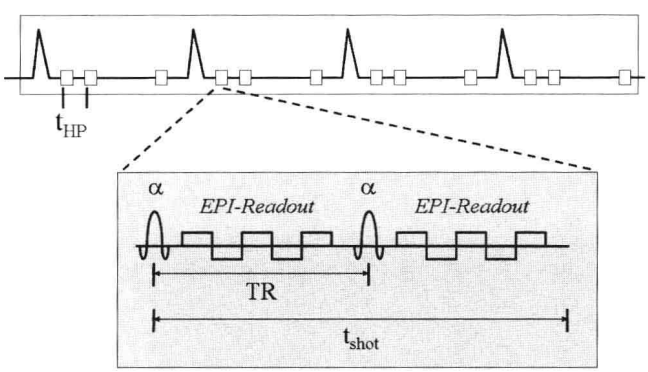


Figure 1.5. Schematic diagram of the basic principle of a turbo field echo-planar MR sequence (TFEPI) in relation to the timing within the cardiac cycle. After each rf excitation pulse (α), in this case five lines in k-space are acquired (EPI factor 5), which is repeated two times per shot (turbo-factor 2), leading to a total of 10 acquired k-lines per heart phase image segment per cardiac cycle (gray area). In total, 4 heart beats are shown, resulting in an image of 40 k-lines. Suppose an image of 120 k-lines is required, the procedure needs to be repeated three times, leading to a total of heart beats of 12. With a heart rate of 60 beats-per-minute, this can be performed during a breath-hold of 12 seconds. White squares indicate heart phase image segments; t_{HP}, time between each heart phase (temporal resolution); TR, repetition time; t_{shot}, shot duration.

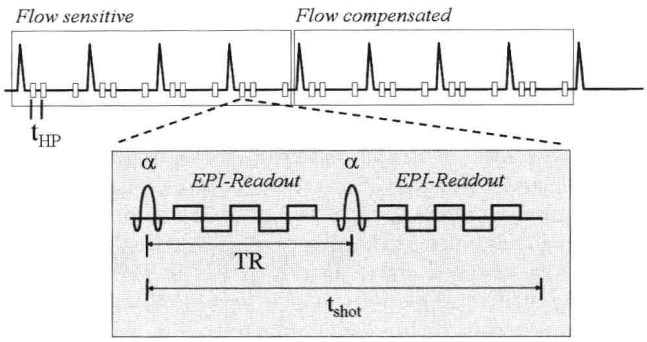


Figure 1.6. Schematic diagram of the basic principle of a turbo field echo-planar MR flow sequence (TFEPI flow) in relation to the timing within the cardiac cycle. After each rf excitation pulse (α), in this case five lines in k-space are acquired (EPI factor 5), which is repeated two times (turbo-factor 2), leading to a total of 10 acquired k-lines per heart phase image segment per cardiac cycle (gray area). In total, 4 heart beats are shown for the flow sensitive image, as well as 4 heart beats for the flow compensated image, resulting in images of 40 k-lines for each image type. Suppose the images require 120 k-lines for a sufficiently high spatial resolution, the procedure needs to be repeated three times, leading to a total of heart beats of 24. With a heart rate of 60 beats-per-minute, this can be performed during a breath-hold of 24 seconds. White squares indicate heart phase image segments; t_{HP}, time between each heart phase (temporal resolution); TR, repetition time; t_{shot}, shot duration.

A major problem for clinical application of cardiac CVMR is the practical worry of obtaining a reliable ECG signal from a patient inside the MR scanner. In about 2% to 5% of clinical cases no reliable ECG signal may be obtained. The electrical ECG signal is distorted by the interaction of the magnetic field and the pulsating blood flow through the aortic arch (magneto hemodynamic effect). Recently, a new approach was launched to correct this problem. The vector ECG (VCG) is based on the three-dimensional orientation of the QRS complex and T wave of the ECG and the distorting component (7). The MR acquisition can be triggered by the QRS-complex only and not by mistake by the T-wave or ECG distortions or by the signal induced by gradient switching. The VCG, in conjunction with the dedicated cardiac synergy surface coil and SENSE, has revolutionized clinical application of CVMR (Fig. 1.1). Today no practical limitation for CVMR exists, except for the conventional MR exclusion criteria, such as unstable or sensitive, implanted metal objects or pregnancy.

RESPIRATORY MOTION COMPENSATION

A second source of image distortion is respiratory motion. A decade ago, MR acquisitions were so time-consuming that it was impossible to perform breath-hold imaging. At that time, an inventive technique was introduced called ROPE (respiratory ordered phase encoding) (8) or PEAR (phase encoding artifact reduction), which was based on a special k-line reordering technique, combined with a respiratory tracking device around the abdomen. By positioning acquired k-lines during breathing in the periphery of k-space (the part that is less sensitive to motion), breathing artifacts were decreased. This type of artifact reduction improved image quality but was not yet optimal because of the indirect relation between abdominal movement and the actual heart motion.

Due to development of faster MR imaging techniques, such as echo-planar imaging and turbo-field echo imaging, it became possible to acquire image data during a short breath-hold of around 15 seconds. The general disadvantage of breath-hold acquisitions is that the reproducibility of the breath-hold level is not optimal. In a multislice, multiple breath-hold acquisition this may introduce errors in, for example, the summed end-diastolic volume of different slices that were acquired during different breath-holds. Without proper patient instruction, this can lead to high variability in the measurements or, even worse, to inaccurate clinical data. So when using breath-hold acquisitions, carefully instructing the patient to hold his breath in expiration is necessary, which minimizes the previously mentioned problem of breath-hold level reproducibility.

Some high-resolution MR acquisitions require longer acquisition times than possible during a breath-hold. For example, coronary artery MR angiography can be performed during a short breath-hold, but the optimal quality can be obtained by using the respiratory navigator technique only (9,10). Respiratory navigation is based on a one-dimensional image positioned at the interface between lung and liver, and the motion of the diaphragm can be tracked. Usually, the navigator beam is positioned on the right hemidiaphragm (Fig. 1.7) and is acquired before and after every MR data acquisition block (Fig. 1.8), with an acquisition duration of only 30 milliseconds. The acquisition is then gated to the automatically traced breathing signal derived from the respiratory navigator. A window around the end-expiration position of the diaphragm is defined, determining the positions in which MR data is accepted. For example, a 3-mm acceptance window means that in end-expiration a 3-mm motion is accepted. Respiratory navigators can also be used for slice

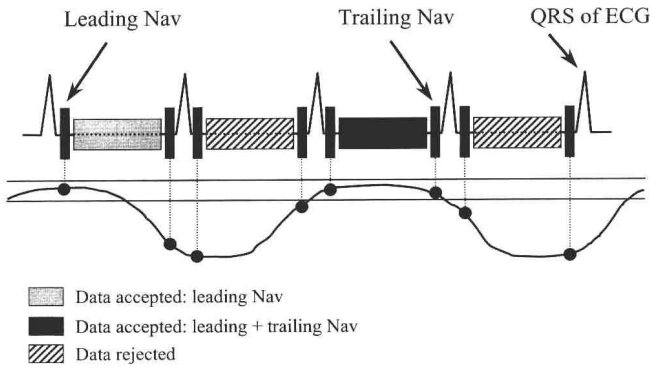


Figure 1.8. The MR acquisition is gated to a predefined acceptance window (*two solid horizontal lines*) based on the traced respiratory signal (*curved solid line*) around end-expiration. K-space data are acquired continuously, but only data are stored that fulfill the requirement that (a) before data acquisition, the navigator was within the acceptance window (leading navigator); or that (b) before and after data acquisition, the navigator was within the acceptance window (leading and trailing navigator). Other acquired image data are deleted. This is the principle of a real-time prospective respiratory navigator.

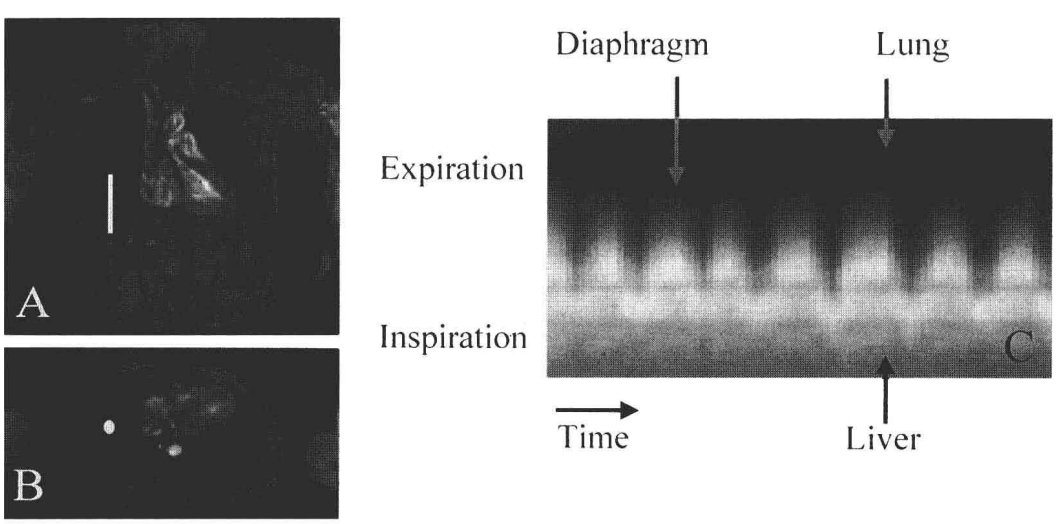


Figure 1.7. The respiratory navigator pencil beam (*A, white line; B, white dot*) is positioned on the right hemidiaphragm at the interface between lung and liver, based on a survey image in the coronal **(A)** and sagittal **(B)** planes. The one-dimensional navigator image is acquired repeatedly over time, thereby constructing an image of diaphragmatic motion **(C)**. The edge between lung and liver is traced automatically, yielding a breathing curve similar to that represented in the diagram of Figure 1.8.