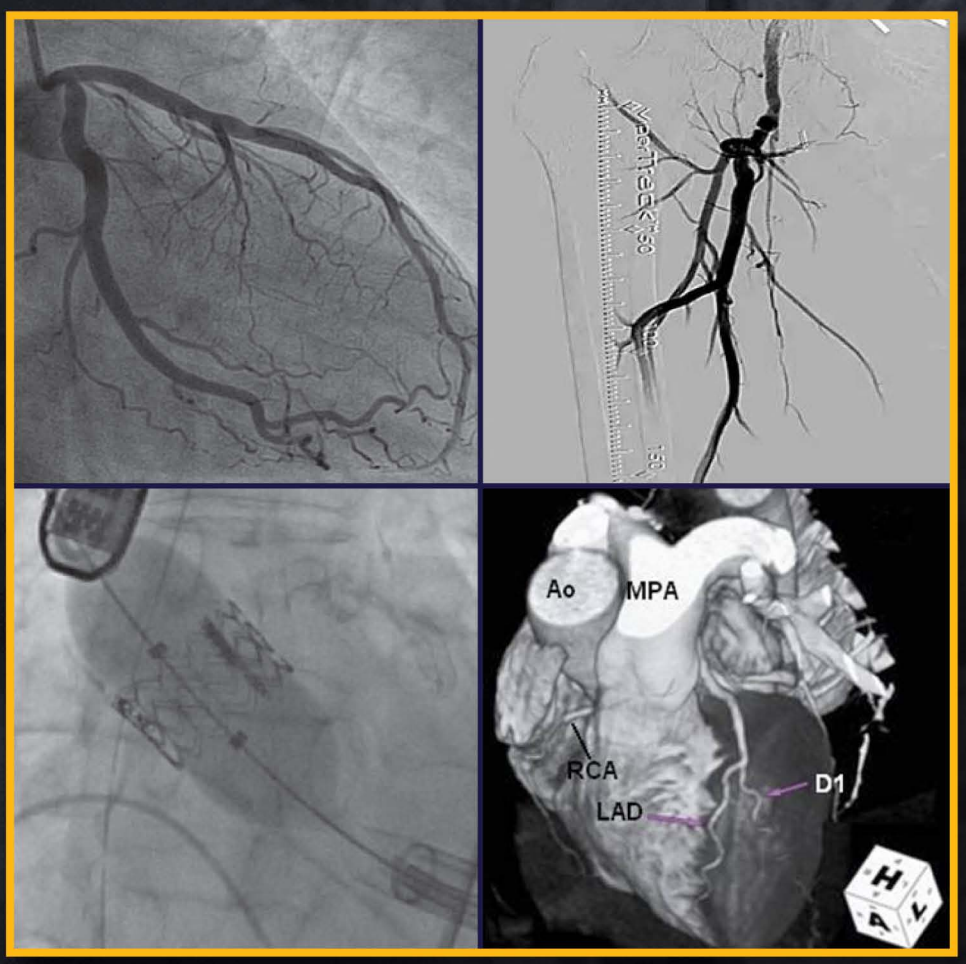
SECOND EDITION

Cardiovascular Catheterization and Intervention

A Textbook of Coronary, Peripheral, and Structural Heart Disease



Edited by
Debabrata Mukherjee • Eric R. Bates
Marco Roffi • Richard A. Lange • David J. Moliterno

CRC Press
Taylor & Francis Group

Cardiovascular Catheterization and Intervention

A Textbook of Coronary, Peripheral, and Structural Heart Disease

Second Edition

Cardiovascular Catheterization and Intervention

A Textbook of Coronary, Peripheral, and Structural Heart Disease

Second Edition

Edited by

Debabrata Mukherjee

Eric R. Bates

Marco Roffi

Richard A. Lange

David J. Moliterno

Managing Editor

Nadia M. Whitehead

CRC Press

Taylor & Francis Group

Boca Raton London New York

CRC Press is an imprint of the
Taylor & Francis Group, an **informa** business

CRC Press
Taylor & Francis Group
6000 Broken Sound Parkway NW, Suite 300
Boca Raton, FL 33487-2742

Printed on acid-free paper

International Standard Book Number-13: 978-1-4987-5019-6 (Pack – Hardback and eBook)

Library of Congress Cataloging-in-Publication Data

Names: Mukherjee, Debabrata, editor. | Bates, Eric R., editor. | Roffi, Marco, editor. | Lange, Richard A., editor. | Moliterno, David J., editor.
Title: Cardiovascular catheterization and intervention / [edited by] Debabrata Mukherjee, Eric R. Bates, Marco Roffi, Richard Lange, David J. Moliterno.
Other titles: Cardiovascular catheterization and intervention (Mukherjee)
Description: Second edition. | Boca Raton, FL : CRC Press/Taylor & Francis Group, 2018. | Includes bibliographical references and index.
Identifiers: LCCN 2017006001| ISBN 9781498750196 (pack-hardback and ebook : alk. paper) | ISBN 9781498750264 (ebook) | ISBN 9781498752169 (ebook) | ISBN 9781498752671 (ebook)
Subjects: | MESH: Cardiac Catheterization--methods | Cardiovascular Diseases--diagnosis | Cardiovascular Diseases--therapy | Catheterization, Peripheral--methods | Coronary Angiography--methods
Classification: LCC RC683.5.C25 | NLM WG 141.5.C2 | DDC 616.1/20754--dc23
LC record available at https://lccn.loc.gov/2017006001

Visit the Taylor & Francis Web site at
http://www.taylorandfrancis.com

and the CRC Press Web site at
http://www.crcpress.com

Dedication

To all the cardiology fellows who enrich my academic experience every day, to my parents who continue to inspire me, to wonderful Suchandra for her love, friendship, and support, and to my beloved nephew, Rohin Hegde.

Debabrata Mukherjee

I would like to thank my wife, Nancy, and children, Andrew, Lyndsay, Alexis, and Evan, for all their love and support during the writing of this book.

Eric R. Bates

To my spouse, Muriel, and our children, Emma, Thomas, Giulia, and Edouard, with love and gratitude.

Marco Roffi

The truly important matters of the heart have been imparted to me by my parents, my lovely wife, Bobette, and our three sons—David, Jonathan, and Brian. My dedication is to them, as my love and admiration for them is ineffable.

Richard A. Lange

To my loving wife, Judith, and our sons, Nathaniel and Benjamin, of whom I am forever proud.

David J. Moliterno

Contents

Preface

The field of interventional cardiovascular medicine continues to rapidly evolve in both the diagnostic and therapeutic arenas. Over the past decade, substantial advances have been made on many fronts, including the development and utilization of techniques and devices for intravascular and intracardiac imaging, percutaneous hemodynamic support, newer drug-eluting stents, drug-coated balloons, and percutaneous valve repair and replacement. The evolution of newer drugs and devices challenges the cardiologist to stay abreast of cutting-edge pharmacological and mechanical strategies for optimal patient care. The second edition of *Cardiovascular Catheterization and Intervention: A Textbook of Coronary, Peripheral, and Structural Heart Disease* aims to provide clinicians with comprehensive guidance on the preprocedural, procedural, and postprocedural aspects of coronary, peripheral, and structural heart disease interventions. The text features evidence-based discussions on patient selection, vascular access, general principles of interventional cardiology, and postprocedure management of these patients; it also serves as a comprehensive, easily accessible reference for busy practitioners and cardiovascular trainees.

Of foremost importance, the topic areas covered are relevant to the daily practice of interventional cardiology. The book begins with several chapters dedicated to key concepts associated with cardiac catheterization and interventional cardiovascular medicine. The subsequent chapters focus on hemodynamic assessment and coronary angiography in general and in specific situations, such as those in pediatric patients and in adults with congenital heart disease. The bulk of the text addresses coronary and noncoronary interventions, including structural heart disease interventions. Finally, we have included dedicated chapters on credentialing and organizing prehospital and hospital systems that focus on cardiovascular care. A large number of high-quality illustrations make this textbook particularly attractive to the practitioner.

Essential to the quality and appropriateness of the text is the expertise of the chapter authors. We are fortunate to have assembled a stellar roster of interventional cardiovascular experts to create this book. The contributing authors from leading medical centers around the world have collectively performed hundreds of thousands of procedures and have published thousands of peer-reviewed manuscripts. We are greatly indebted to them. The practice of interventional cardiovascular medicine is exciting, rewarding, and a privilege that each of us enjoys. Likewise, it has been our personal honor to work with these superb contributors, our colleagues in interventional cardiology, as well as the editorial team at CRC Press. It is our hope that you will enjoy this book and that it will be a valuable resource to you in providing the highest quality of care to your patients.

Debabrata Mukherjee
Texas Tech University Health Sciences Center El Paso

Eric R. Bates,
University of Michigan

Marco Roffi
University Hospital of Geneva, Switzerland

Richard A. Lange
Texas Tech University Health Sciences Center El Paso

David J. Moliterno
University of Kentucky

Editors

Debabrata Mukherjee, **MD**, is a Professor and Chair of Internal Medicine and Chief of Cardiovascular Medicine at Texas Tech University Health Sciences Center El Paso (TTUHSC El Paso) in El Paso, Texas.

Eric R. Bates, MD, is a Professor of Internal Medicine at the University of Michigan, Ann Arbor.

Marco Roffi, MD, is a Professor of Medicine, Vice-Chariman of Cardiology, and Director of the Interventional Cardiology Unit at the University Hospital of Geneva, Switzerland.

Richard A. Lange, MD, MBA, is President of TTUHSC El Paso and Dean of the Paul L. Foster School of Medicine at TTUHSC El Paso in El Paso, Texas.

David J. Moliterno, MD, is a Professor and Chair of Internal Medicine at the University of Kentucky, Lexington.

Contributors

Aamer Abbas MD
Heart and Vascular Center at Titus, Titus Regional Medical Center, Mount Pleasant, Texas, USA

J. Dawn Abbott MD
Cardiovascular Institute, Rhode Island Hospital, Warren Alpert Medical School, Brown University, Providence, Rhode Island, USA

Shikhar Agarwal MD MPH
Interventional Cardiology and Structural Interventions, Geisinger Medical Center, Danville, Pennsylvania, USA

Jorge R. Alegria MD
Sanger Heart & Vascular Institute, Carolinas HealthCare System, Charlotte, North Carolina, USA

Syed Sohail Ali MD
Toledo Cardiology Consultants, Toledo, Ohio, USA

Basil Alkhatib MD
College of Medicine, The University of Arizona, Phoenix, Arizona, USA

Guilherme F. Attizzani MD
Cardiovascular Imaging Core Laboratory, Cardiac Catheterization Laboratory, University Hospitals Cleveland Medical Center, Case Western Reserve University School of Medicine, Cleveland, Ohio, USA

Sawsan Mokhtar M. Awad MD MSc
Rush University Medical Center, Rush Center for Congenital and Structural Heart Disease, Chicago, Illinois, USA

Steven R. Bailey MD
Janey and Dolph Briscoe Division of Cardiology, Long School of Medicine, University of Texas Health Science Center at San Antonio, San Antonio, Texas, USA

Sumit Baral MD
Icahn School of Medicine at Mount Sinai, Mount Sinai Hospital, New York, New York, USA

Thomas M. Bashore MD
Division of Cardiology, Duke University Medical Center, Durham, North Carolina, USA

Chirag Bavishi MD MPH
Department of Cardiology, Mount Sinai St Luke's, New York, New York, USA

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

Martin R. Bennett MD PhD
Division of Cardiovascular Medicine, University of Cambridge, Cambridge, United Kingdom

Hiram G. Bezerra MD PhD
Cardiovascular Imaging Core Laboratory, Cardiac Catheterization Laboratory, University Hospitals Cleveland Medical Center, Case Western Reserve University School of Medicine, Cleveland, Ohio, USA

Ion Botnaru MD
Olympia Multi-specialty Clinic, Olympia, Washington, USA

Adam J. Brown MD PhD
Division of Cardiovascular Medicine, University of Cambridge, Cambridge, United Kingdom

Adriano Caixeta MD PhD
Hospital Israelita Albert Einstein, Escola Paulista de Medicina, Universidade Federal de São Paulo, São Paulo, Brazil

Qi-Ling Cao MD
Echo and Research Lab, Sidra Cardia Program, Department of Pediatrics, Sidra Medical and Research Center, Doha, Qatar

Blase A. Carabello MD
East Carolina Heart Institute, Brody School of Medicine, East Carolina University, Greenville, North Carolina, USA

John D. Carroll MD
Division of Cardiology, School of Medicine, University of Colorado, Aurora, Colorado, USA

Joseph P. Carrozza Jr. MD
Tufts University School of Medicine,
St. Elizabeth's Medical Center,
and
Steward Health Care Cardiovascular Network, Boston, Massachusetts, USA

Saurav Chatterjee MD
Interventional Cardiology, Temple University Hospital, Philadelphia, Pennsylvania, USA

Jack P. Chen MD
Northside Heart and Vascular Institute, Northside Hospital, Atlanta, Georgia, USA

Leslie Cho MD
Women's Cardiovascular Center, Preventive Cardiology & Rehabilitation, Cleveland Clinic Foundation, Cleveland, Ohio, USA

Marco A. Costa MD PhD
Harrington Heart & Vascular Institute, Interventional Cardiovascular Center, University Hospitals Cleveland Medical Center, Case Western Reserve University School of Medicine, Cleveland, Ohio, USA

Charis Costopoulos MD MPhil
Division of Cardiovascular Medicine, University of Cambridge, Cambridge, United Kingdom

Fernando Cura MD
Cardiology Clinic, Cardiovascular Institute of Buenos Aires, Anchorena Hospital, Buenos Aires, Argentina

Charles J. Davidson MD
Division of Cardiology, Department of Medicine, Bluhm Cardiovascular Institute, Northwestern University Feinberg School of Medicine, Chicago, Illinois, USA

Laura Davidson MD
Division of Cardiology, Department of Medicine, Bluhm Cardiovascular Institute, Northwestern University Feinberg School of Medicine, Chicago, Illinois, USA

Gregory J. Dehmer MD
Division of Cardiology, Baylor Scott & White Health, Texas A&M College of Medicine, Temple, Texas, USA

Victoria Delgado MD PhD
Department of Cardiology, Leiden University Medical Center, Leiden, The Netherlands

José G. Díez MD
Interventional Cardiology, Baylor College of Medicine, Texas Heart Institute, Houston, Texas, USA

Steven P. Dunn PharmD
Heart and Vascular Center, University of Virginia Health System, University of Virginia School of Medicine, Charlottesville, Virginia, USA

Franz R. Eberli MD
Division of Cardiology, Triemli Hospital Zurich, Zurich, Switzerland

John P. Erwin MD
Division of Cardiology, Baylor Scott & White Health, Texas A&M College of Medicine, Temple, Texas, USA

Amir-Ali Fassa MD
Department of Cardiology, La Tour Hospital, Geneva, Switzerland

Stefano Galli MD
Centro Cardiologico Monzino, Milan, Italy

Joel A. Garcia Fernandez MD
Orlando Health Heart Institute, Orlando, Florida, USA

Irakli Gogorishvili MD
Jo Ann Medical Centre, T'bilisi, Georgia

Mario Gössl MD PhD
Minneapolis Heart Institute, Abbott Northwestern Hospital, Minneapolis, Minnesota, USA

Matthias Greutmann MD
Department of Cardiology, University Heart Center, University Hospital Zurich, Zurich, Switzerland

Paul Michael Grossman MD
Frankel Cardiovascular Center, University of Michigan, Ann Arbor, Michigan, USA

Christiane Gruner MD
Department of Cardiology, University Heart Center, University Hospital Zurich, Zurich, Switzerland

Evan L. Hardegree MD
Division of Cardiology, Baylor Scott & White Health, Temple, Texas, USA

Ziyad M. Hijazi MD MPH
Weil Cornell Medical College, Cornell University,
and
Department of Pediatrics, Sidra Medical and Research Center, Doha, Qatar

John W. Hirshfeld Jr. MD
Penn Heart and Vascular Center, Perelman School of Medicine, University of Pennsylvania, Philadelphia, Pennsylvania, USA

Claudia P. Hochberg MD
The Cardiovascular Center, Boston Medical Center, Boston, Massachusetts, USA

Eric Horlick MDCM
Peter Munk Cardiac Centre, Toronto General Hospital, University Health Network, Toronto, Canada

Nay Htyte MD
NYU Cardiac Catheterization Associates, New York University, Langone Medical Center, New York, New York, USA

Arif Jivan MD
Division of Cardiology, Feinberg School of Medicine, Northwestern University, Chicago, Illinois, USA

Brinder Kanda MD
Minneapolis Heart Institute, Abbott Northwestern Hospital, Minneapolis, Minnesota, USA

David E. Kandzari MD
Piedmont Heart Institute, Piedmont Healthcare, Atlanta, Georgia, USA

Samir R. Kapadia MD
Department of Cardiovascular Medicine, Cleveland Clinic Foundation, Cleveland, Ohio, USA

Subrata Kar DO
Department of Internal Medicine, Paul L. Foster School of Medicine, Texas Tech University Health Sciences Center El Paso, El Paso, Texas, USA

Morton J. Kern MD
Division of Cardiology, Veterans Affairs Long Beach Healthcare System, Long Beach, California, USA
and
University of California, Irvine Medical Center, Orange, California, USA

Spencer B. King, III MD
Emory University School of Medicine, Atlanta, Georgia, USA

Nicholas Kipshidze MD PhD
New York Cardiovascular Research
New York, New York, USA

Amartya Kundu MD
Department of Medicine, University of Massachusetts Medical School, Worcester, Massachusetts, USA

Rony Lahoud MD MPH
Heart and Vascular Institute, Cleveland Clinic Foundation, Cleveland, Ohio, USA

Richard A. Lange MD MBA
Paul L. Foster School of Medicine, Texas Tech University Health Sciences Center El Paso, El Paso, Texas, USA

Michael J. Lim MD
Center for Comprehensive Cardiovascular Care, School of Medicine, Saint Louis University
St. Louis, Missouri, USA

Robert A. Lookstein MD
Division of Vascular and Interventional Radiology, Icahn School of Medicine at Mount Sinai, New York, New York, USA

Tracy E. Macaulay PharmD
College of Pharmacy, University of Kentucky, Lexington, Kentucky, USA

Akiko Maehara MD
Columbia University Medical Center, Cardiovascular Research Foundation, New York, New York, USA

Alberto Maud MD
Department of Neurology, Paul L. Foster School of Medicine, Texas Tech University Health Sciences Center El Paso, El Paso, Texas, USA

Vallerie V. McLaughlin MD
Frankel Cardiovascular Center, University of Michigan, Ann Arbor, Michigan, USA

Bernhard Meier MD
Department of Cardiology, University Hospital of Bern, Bern, Switzerland

Mellita Mezody MD
Peter Munk Cardiac Centre, Toronto Western Hospital, University Health Network, Toronto, Canada

Gary S. Mintz MD
Cardiovascular Research Foundation, New York, New York, USA

David J. Moliterno MD
Gill Heart and Vascular Institute, University of Kentucky, Lexington, Kentucky, USA

Piero Montorsi MD
Department of Clinical Sciences and Community Health, University of Milan, Centro Cardiologico Monzino, Milan, Italy

Motaz Moussa MD
Marietta Memorial Hospital, Memorial Health System, Marietta, Ohio, USA

Debabrata Mukherjee MD
Department of Internal Medicine, Paul L. Foster School of Medicine, Texas Tech University Health Sciences Center El Paso, El Paso, Texas, USA

David W. M. Muller MBBS MD
Department of Cardiology, St. Vincent's Hospital, St. Vincent's Clinical School, University of New South Wales, Sydney, New South Wales, Australia

Srihari S. Naidu MD
Hypertophic Cardiomyopathy Program, Westchester Heart and Vascular Institute, Westchester Medical Center Health Network, New York Medical College, Hawthorne, New York, USA

Jose Andrés Navarro MD
Cardiovascular Institute of Buenos Aires,
Buenos Aires, Argentina

Fabian Nietlispach MD PhD
University Heart Center, University Hospital Zurich, Zurich, Switzerland

Stéphane Noble MD
Division of Cardiology, University Hospital of Geneva, Geneva, Switzerland

Theophilus Owan MD
Division of Cardiovascular Medicine, Department of Internal Medicine, The University of Utah, Salt Lake City, Utah, USA

Akhil Parashar MD
Department of Internal Medicine, Cleveland Clinic Foundation, Cleveland, Ohio, USA

Myung H. Park MD
Houston Methodist DeBakey Heart & Vascular Center, Houston Methodist Hospital, Houston, Texas, USA

Gabriel Tensol Rodrigues Pereira MD
Cardiovascular Imaging Core Laboratory, Harrington Heart & Vascular Institute, University Hospitals Cleveland Medical Center, Cleveland, Ohio, USA

Raffaele Piccolo MD
Department of Cardiology, University Hospital of Bern, Bern, Switzerland

Mark J. Ricciardi MD
Cardiac Catheterization Labs and Interventional Cardiology, Northwestern Bluhm Cardiovascular Institute, Northwestern University Feinberg School of Medicine, Chicago, Illinois, USA

Albert P. Rocchini MD
Department of Pediatrics, University of Michigan, C.S. Mott Children's Hospital, Ann Arbor, Michigan, USA

Gustavo J. Rodriguez MD
Department of Neurology, Paul L. Foster School of Medicine, Texas Tech University Health Sciences Center El Paso, El Paso, Texas, USA

Marco Roffi MD
Division of Cardiology, University Hospital of Geneva, Geneva, Switzerland

Robert J. Rosen MD
Lenox Hill Heart and Vascular Institute, New York, New York, USA

Gregg F. Rosner MD
Division of Cardiovascular Medicine, Columbia University Medical Center, New York, New York, USA

John H. Rundback MD
Interventional Institute, Holy Name Medical Center, Advanced Interventional Radiology Svcs LLP, Teaneck, New Jersey, USA

Fadi A. Saab MD
Michigan State University,
and
Pulmonary Embolism and DVT Program, Department of Cardiovascular Medicine, University of Michigan Health, Grand Rapids, Michigan, USA

Robert D. Safian MD
Center for Innovation and Research in Cardiovascular Diseases, Department of Cardiovascular Medicine, Beaumont Health, Royal Oak, Michigan, USA

M. Rizwan Sardar MD
Division of Cardiology, Warren Alpert Medical School, Brown University, Providence, Rhode Island, USA

Partha Sardar MD
Division of Cardiovascular Medicine, The University of Utah, Salt Lake City, Utah, USA

Arnold H. Seto MD
Division of Cardiology, Veterans Affairs Long Beach Healthcare System, Long Beach, California, USA
and
University of California, Irvine Medical Center, Orange, California, USA

Richard W. Smalling MD PhD
Division of Cardiovascular Medicine, McGovern Medical School, University of Texas Health Science Center at Houston,
and
Memorial Hermann Heart and Vascular Institute, Houston, Texas, USA

Athanasios Smyrlis MD
South Nassau Cardiac Care, South Nassau Communities Hospital, Oceanside, New York, USA

Amirreza Solhpour MD
Division of Cardiovascular Medicine, McGovern Medical School, University of Texas Health Science Center at Houston and
Memorial Hermann Heart and Vascular Institute, Houston, Texas, USA

Paul Sorajja MD
Center for Valve and Structural Heart Disease, Minneapolis Heart Institute, Abbott Northwestern Hospital, Minneapolis, Minnesota, USA

Mohamad Soud MD
Cardiovascular Imaging Core Laboratory, Harrington Heart & Vascular Institute, University Hospitals Cleveland Medical Center, Cleveland, Ohio, USA

Roberto Spina MBBS MS
Department of Cardiology, St. Vincent's Hospital, Sydney, New South Wales, Australia

Garrick C. Stewart MD MPH
Division of Cardiovascular Medicine, Brigham and Women's Hospital, Boston, Massachusetts, USA

Saad Hussain Syed MD
Department of Internal Medicine, Paul L. Foster School of Medicine, Texas Tech University Health Sciences Center El Paso, El Paso, Texas, USA

James E. Tcheng MD
Division of Cardiology, Duke University School of Medicine, Duke University Health System, Durham, North Carolina, USA

Carl L. Tommaso MD
Cardiac Catheterization Laboratory, NorthShore University HealthSystem, Rush Medical School Evanston, Illinois, USA

Laurens F. Tops MD PhD
Department of Cardiology, Leiden University Medical Center, Leiden, The Netherlands

E. Murat Tuzcu MD
Department of Cardiovascular Medicine, Cleveland Clinic Abu Dhabi, Abu Dhabi, United Arab Emirates

Zoltan G. Turi MD
Seton Hall University School of Medicine, Structural Heart Program and Cardiac Catheterization Laboratory, Hackensack University Medical Center, New Brunswick, New Jersey, USA

Dennis W. den Uijl MD PhD
Department of Cardiology, Leiden University Medical Center, Leiden, The Netherlands

Michele Doughty Voeltz MD
Henry Ford Health System, Detroit, Michigan, USA

Peter Wenaweser MD
Department of Cardiology, University Hospital of Bern, Cardiovascular Center Zurich, Hirslanden Clinic in the Park, Bern and Zurich, Switzerland

Christopher J. White MD
Department of Cardiology, Ochsner Medical Center, New Orleans, Louisiana, USA

David O. Williams MD
Harvard Medical School, Cardiovascular Division, Brigham and Women's Hospital, Boston, Massachusetts, USA

James M. Wilson MD
Interventional Cardiology, Houston, Texas, USA

Stephan Windecker MD
Department of Cardiology, University Hospital of Bern, Bern, Switzerland

Hong Jun Yun MD
Frankel Cardiovascular Center, University of Michigan, Ann Arbor, Michigan, USA

PART 1

General Concepts

1

Introduction to cardiac catheterization

RICHARD A. LANGE AND STEVEN R. BAILEY

INTRODUCTION

Cardiac catheterization is one of the most frequently performed procedures in the United States. Over the past 25 years, the number of procedures has increased 3.5-fold because of expanded indications and improvements in techniques and equipment.[1] In 2005, an estimated 1,322,000 inpatient left heart diagnostic catheterizations and 1,271,000 inpatient percutaneous coronary interventional (PCI) procedures were performed in the United States.[1] According to the most recent American Hospital Association survey, 36% of the 4,836 hospitals in the United States have adult diagnostic catheterization laboratories. Of the 1,728 hospital-centered adult diagnostic laboratories, 78% are PCI capable.[2]

Historical perspective

THE EARLY YEARS OF CATHETERIZATION: ANIMAL AND CADAVERIC STUDIES (1711–1927)

The earliest known cardiac catheterization of an animal was performed in 1710 by Reverend Stephen Hales, an English physiologist and parson, who "bled a sheep to death and then led a gun barrel from the neck vessels into the still beating heart. Through this, he filled the hollow chambers with molten wax and then measured from the resultant cast the volume of the heartbeat and the minute-volume of the heart, which he calculated from the pulse beat."[3,4] In addition, Hales was the first to determine systemic arterial pressure, when, in 1727, he measured the rise in a column of blood in a long glass tube secured in an artery (Figure 1.1). Brass pipes placed in the carotid artery and jugular vein of a horse were connected to an 11-ft-high glass tube for pressure measurements, with the trachea of a goose used as a flexible connector. Hales astutely noted that the pressure was different in arteries and veins (blood from the carotid artery rose to a height of more than 8 ft in the glass tube, whereas blood from the jugular vein rose less than 1 ft) and between contractions and relaxations of the heart.

In 1844, the term *cardiac catheterization* was coined by Claude Bernard, a French physiologist who inserted long glass thermometers into a horse's right and left ventricles from its jugular vein and carotid artery, respectively. By demonstrating that blood temperature was higher in the right ventricle than in the left, he established that "chemical reactions" (i.e., metabolism) occurred in the body rather than the lungs. Subsequently, he used this technique to acquire blood samples from various arterial and venous sites for metabolic studies, and he performed intracardiac pressure recordings in dogs and sheep to study the regulation of systemic arterial pressure by the nervous system. He was the first to describe right and left heart catheterization via the femoral vein and artery.[5,6] Although Bernard was not the first to perform catheterization, his careful application of scientific methods to the study of cardiac physiology demonstrated the potential importance of cardiac catheterization and initiated an era of cardiovascular physiologic investigation.

In 1861, Etienne Jules Marey, another French physiologist, in collaboration with Jean Baptiste Aguste Chauveau, a veterinarian, elucidated the nature of the apex beat by simultaneously recording its movement and the right atrial and right ventricular pressures of a conscious horse.[7] Their observation that the apical impulse was caused by early forceful ventricular contraction remains a milestone as the first graphic recording of intracardiac events in a conscious animal (Figure 1.2).[8] Gaining access to the left ventricle via the carotid artery, they studied left ventricular pressure waveforms and characterized various phases of the cardiac cycle, and they were the first to obtain simultaneous recordings of left ventricular and aortic pressures. In addition,

Figure 1.1 First documented cardiac catheterization performed by Hales in 1711. (Courtesy of the Bettmann Archives.)

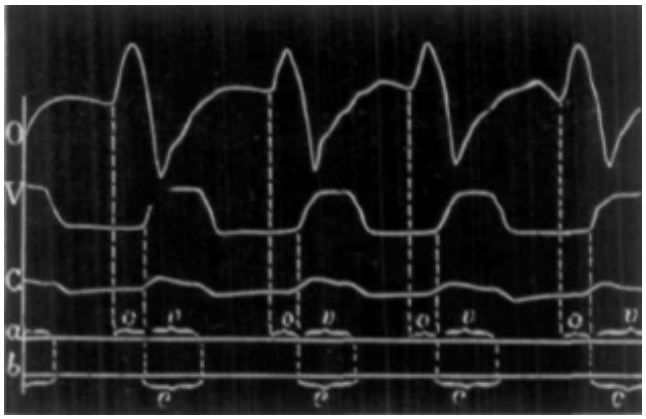


Figure 1.2 First published records of pressure pulses in a cardiac chamber obtained by catheterization of the right atrium (O) and ventricle (V) via the jugular vein in an unanesthetized horse. The third tracing (C) is from an intrathoracic balloon catheter placed to detect the cardiac impulse. (From Chaveau, A., and Marey, É. J., *Circulation Research*, 22, 96, 1968. With permission.)

Marey and Chaveau invented the double-lumen catheter, with which they simultaneously measured pressures in contiguous cardiac chambers in horses and dogs. Decades later, André Cournand (see following text) utilized this catheter design to perform similar studies in humans.

In 1870, Adolph Fick (Figure 1.3), a German physicist and physiologist, proposed a direct method of measuring cardiac output. In a commentary to his local medical society that resulted in a publication less than one page long (the Fick principle, 1870), Fick proposed that the cardiac output could be measured by dividing the oxygen uptake by the corresponding arteriovenous oxygen content difference.[9] Interestingly, in 1873 Fick published the results of right and left heart catheterizations that he performed in animals, but he did not utilize or validate his method.[10] Only two decades later did physiologists begin to apply the Fick principle in animals. Although Grehant and Quinquand published a brief report describing use of the technique in dogs in 1886, it was not until 1898, when Zuntz and Hageman made a detailed study of cardiac output in the horse at rest and during exercise, that the Fick method was established as reliable and reproducible.[11] Application of the Fick principle in humans was hindered by the difficulty of obtaining samples of mixed venous blood. Invasive catheterization was thought to be too dangerous to be applied to human subjects because of excessive blood loss and the risk of infection. Furthermore, radiography was not yet available, so attempts to obtain samples of mixed venous blood were made by such avant-garde interventions as direct transthoracic needle puncture of the right ventricle.[12]

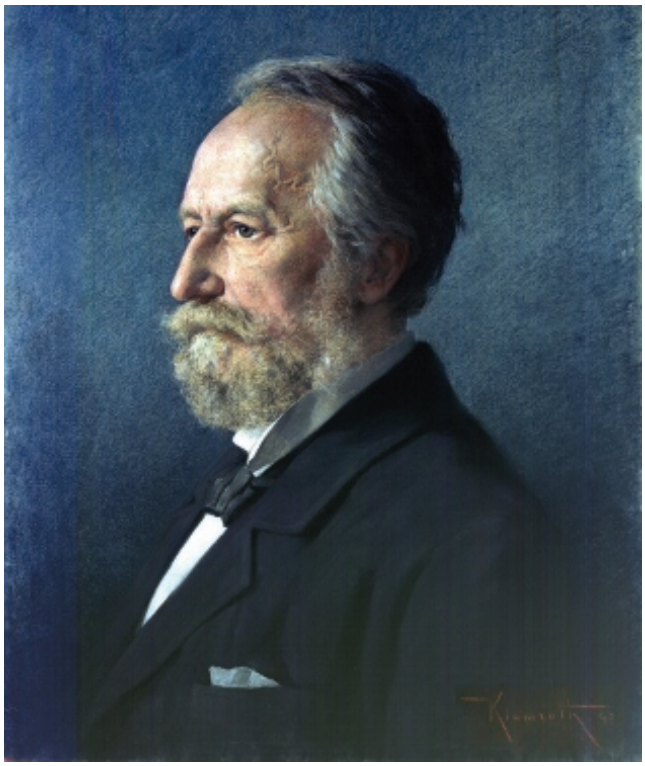


Figure 1.3 Adolph Fick (1829–1901), a mathematician, physicist, and physiologist. His major research interest was in the physiology of muscular contraction. He described the calculation of cardiac output as an outgrowth of his mathematical approach to physiologic events.