# Handbook of Cardiac Anatomy, Physiology, and Devices

# HANDBOOK OF CARDIAC ANATOMY, PHYSIOLOGY, AND DEVICES

Edited by

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Cover design by Patricia F. Cleary.

Cover illustrations: Images were created in the Visible Heart® Laboratory of Professor Iaizzo. *(Upper left)* An external view of an isolated human heart reanimated in vitro. (The heart was obtained via LifeSource as a r esearch gift from an organ donor whose heart was deemed not viable for transplantation.) *(Upper right)* An internal view of the apex of the left ventricle of a human heart; note the high degree of trabeculations. *(Lower right)* Serial endoscopic images showing movements, top-to-bottom, of a tricuspid valve, a pulmonary valve, a mitral valve, and an implanted mechanical aortic valve (left to right, respectively) from within functioning human hearts. *(Lower left)* Images obtained from an in vitro electrical mapping study of an isolated human heart: an EnSite® 3000 catheter is deployed in the left ventricle and a mapping catheter touches the endocardium. To the right is shown an anatomical isopotential map of excitation (voltage changes) and below it two views of constructed isochronal maps (time sequences of depolarization, anterior and posterior views).

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# PREFACE

The medical device industry in the US is growing at an incredibly rapid pace; in fact, today it is as large as the automobile industry in terms of revenues. Not only has our overall understanding of the molecular basis of disease dramatically increased, but so has the number of available devices to treat specific health problems. This is particularly true in the field of cardiac care. Advances in our understanding of disease processes are being made daily, and novel means to treat cardiac diseases are concomitantly being developed. With this rapid growth rate, the biomedical engineer has been challenged to either retool or continue to seek out sources of concise information.

The major impetus for developing the *Handbook of Cardiac Anatomy, Physiology, and Devices* was the need for a major resource textbook for students, residents, and practicing biomedical engineers. Another motivation was to promote the expertise, past and present, in the area of cardiovascular science at the University of Minnesota. As Director of Education for The Lillehei Heart Institute at the University of Minnesota, I believe that this book also represents an outreach opportunity to carry on the Lillehei legacy through the 21st century.

It may be of interest to note that there are several direct and indirect historical connections with C. Walton Lillehei. First, several of the individuals who contributed chapters had the privilege to work with him. Second, there is the connection with Medtronic, Inc.; founder Earl Bakken was one of the first true biomedical engineers, and he worked directly with Lillehei to develop implantable pacemakers at the University of Minnesota. In accordance with this latter collaboration, it turns out that there are numerous individuals currently working at Medtronic Inc. who strongly encouraged the University of Minnesota to develop outreach materials such as the *Handbook of Cardiac Anatomy, Physiology, and Devices*, as well as other educational programs.

More specifically, it was through my collaborations with Tim Laske, Mark Hjelle (my brother-in-law), and Dale Wahlstrom, all from the Cardiac Rhythm Management Division at Medtronic, Inc., who influenced the inception of this book in numerous ways including: (1) the development of the *Visible Heart*® media project in 1997, which is an ongoing effort to visualize functional cardiac anatomy and to make such images available for instruction; (2) the creation of the Physiology Industrial Advisory Board, which evaluated and subsequently created outreach programs to serve the greater local biomedical industry; and (3) the creation of the week-long short course, Advanced Cardiac Physiology and Anatomy, which was designed specifically for the biomedical engineer working in industry. Importantly, this course has been taught at the University of Minnesota for the past four years and is the basis of this textbook (the senior authors of most chapters present lectures in the course). Over the years, I have fielded numerous requests by engineers who have taken this course to develop more formal reference materials. In addition, many of the numerous Medtronic employees who have visited the *Visible Heart*® laboratory (over 500 individuals, with many repeat visits, in the past seven years) have routinely emphasized the need for advanced training opportunities in systems physiology, specifically for the seasoned biomedical employee. One last historical note of interest: my current laboratory (*Visible Heart*® laboratory), where isolated heart studies are performed weekly, is the same laboratory where C. Walton Lillehei and his many esteemed colleagues conducted a majority of their cardiovascular research studies in the late 1950s and early 1960s.

An added feature of this book that I hope will enhance its utility is a CD containing the *Visible Heart*® Viewer, which was developed as a joint venture between my laboratory at the University of Minnesota and the Cardiac Rhythm Management Division at Medtronic, Inc. An second *Companion CD* also contains various additional color images and movies that were provided by the authors to supplement their chapters.

Importantly, the accompanying media includes functional images of human hearts. These images were obtained from hearts made available via LifeSource, and more specifically through the generosity of families and individuals who made the final gift of organ donation (their hearts were not deemed viable for transplantation).

**Acknowledgments**

I would like to thank Medtronic, Inc. for their continued support of this collaborative project over the past seven years, and I especially acknowledge the commitment, partnership, and friendship of Tim Laske and Dale Wahlstrom, which has made our research possible. In addition, I would like to thank Jilean Dagenais and Mike Leners for their creative efforts in producing many of the movie and animation clips found on the *Companion CD*.

It is also my pleasure to thank the past and present graduate students who have worked in my laboratory and have also been contributors to this text, including: Edward Chinchoy, James Coles, Anthony Dupre, Kevin Fitzgerald, Alexander Hill, Ryan Lahm, Timothy Laske, Anna Legreid, Michael Loushin, Daniel Sigg, Nicholas Skadsberg, and Sarah Vincent. I feel extremely fortunate to have had the opportunity to work with such talented scientists and engineers. I have learned a great deal from each of them.

I would like to acknowledge the exceptional efforts of our Lab Coordinator, Monica Mahre, who: (1) assisted me in coordinating the efforts of the contributing authors; (2) skillfully incorporated my editorial changes; (3) verified the readability and formatting of each chapter; (4) pursued requested additions or missing materials for each chapter; (5) contributed as a coauthor; and (6) kept a positive outlook throughout. I would also like to thank Dee McManus for coordinating the support of

the Lillehei Heart Institute in their funding of illustrator Martin Finch, who prepared several of the original figures; Gary Williams for his computer expertise and assistance with numerous figures; William Gallagher and Charles Soule, who made sure the laboratory kept running smoothly while many of us were busy writing or editing; Dick Bianco for his support of our lab and this book project; the Chairman of the Department of Surgery, Dr. David Dunn, for his support and encouragement; and the Biomedical Engineering Institute at the University of Minnesota, headed by Dr. Jeffrey McCullough, who supported this project by funding the Cardiovascular Physiology Interest Group (most of whose members contributed chapters).

Finally, I would like to thank my family and friends for their support of my career and their assistance over the years. Without such encouragement, I would not have even dreamed of taking on such an ambitious project. Specifically, I would like to thank my wife Marge, my three daughters, Maria, Jenna, and Hanna, my mom Irene, and siblings, Mike, Chris, Mark, and Susan, for always being there for me. On a personal note, some of my motivation for working on this project comes from the memory of my father Anthony, who succumbed to sudden cardiac death at too early an age, and from the positive encouragement of my uncle Tom Halicki, who is doing well seven years after a heart transplant.

***Paul A. Iaizzo, PhD***

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# COMPANION CD

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The Visible Heart®, a CD accompanying *Handbook of Cardiac Anatomy, Physiology, and Devices*, is designed to be a self-contained electronic textbook, developed via a collaboration between the University of Minnesota Medical School and Medtronic, Inc. It utilizes Visible Heart® technologies, a significant advancement in the modeling of the isolated heart that allows display of full-motion images captured from inside the endocardium of the functioning large mammalian heart.

With the support of LifeSource, The Visible Heart® presents images obtained from human hearts donated by generous individuals, whose final acts continue to enhance our understanding of the inner workings of the human heart and to contribute to lifesaving advances in cardiac medicine.

All images and videos on The Visible Heart® were captured in the laboratory of Dr. Iaizzo, utilizing the Visible Heart® technologies that are subject to pending US Patent Application No. 09/419,271 filed October 15, 1999 and PCT Application No. US99/24791, filed October 22, 1999 by the University of Minnesota and Medtronic, Inc.