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# Handbook of Cardiac Anatomy, Physiology, and Devices



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Paul A. Iaizzo  
Editor

# Handbook of Cardiac Anatomy, Physiology, and Devices

Third Edition

 Springer

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## Foreword

In the course of one's professional life, you may be fortunate to encounter an opportunity that brings new clarity to your approach to business. I had such an experience in 1997, when three people—Dr. Paul A. Iaizzo, Tim Laske, and Mark Hjelle—walked into my office and started talking about reanimating porcine hearts on the bench, as a training tool for engineers and scientists working on medical devices. I had no idea what they were talking about, and I did not really know Dr. Paul A. Iaizzo, a professor at the University of Minnesota. But I did know Tim Laske and Mark Hjelle, who are two of the most creative engineers I have ever met. I trust their judgment and their skills. The trio's story, vision, and declaration of what could be achieved were compelling. I was cautious, however, because, to that point in time, our ability to work effectively in partnership with universities was nothing to write home about...except to complain.

Nonetheless, we were always looking for better ways to educate our employees engaged in research, design, or manufacturing of medical products. Clinical applicability is the name of the game for any medical product, but it is very easy for scientists and engineers to design without fully understanding the environment in which their products are being used. This is true in all industries. Lack of understanding of the specific application creates mediocrity in performance. Because of the increasing complexity of the products required to support the rapidly growing tachycardia and resynchronization therapies, we were feeling the pressure to “up our game.” If Tim and Mark believed that Dr. Iaizzo could do what he was proposing, I had no choice but to say yes, and we provided the seed money to get the Visible Heart® laboratory off the ground. Little did I realize at the time what “the trio” and the University of Minnesota team were about to accomplish.

Throughout this book, you will see many images and videos of what the heart prep at the University of Minnesota's Visible Heart Lab can produce. The results of Professor Iaizzo and his research team exceeded my most optimistic projections of the value of the investment. The Visible Heart Lab brings a new depth of understanding to what actually is going on inside beating animal and human hearts. It has helped to reshape how the industry designs and evaluates products. It changed how we made decisions on products to fund or not fund and impacted how we ran our business. In advocating for the investment, Tim Laske, Mark Hjelle, and I made one mistake—we underestimated what Dr. Iaizzo and his team were capable of accomplishing. We would not make that mistake again. I do not believe failure is ever considered as an option by his team.

However, as fantastic as the Visible Heart prep is by itself, it is not the most valuable product of the Visible Heart Lab. I am in awe of Dr. Iaizzo, his team, and industry partners who worked so hard to master the reanimation of hearts. The quality and educational value of the videos and images that they produce are amazing and unbelievably impactful. But the real “gems” of the Visible Heart Lab are the students who graduate every year and go out into the world. The heart prep experience is the core of their training. It is where the students get a chance to “put it all together” in their minds. The training they receive along the way in physiology, biochemistry, instrumentation, tissue engineering, genetics, core biology, and many other related disciplines is unparalleled in my experience. You will see both the basic and applied nature of their education and research as you read this book.

It was clear to me the first time we brought one of these students into our company that they were not the “normal” new graduates. Within weeks after graduating and coming to work at Medtronic, they were providing advice on cardiac anatomy and function to seasoned scientists and engineers who had been designing complex products and bringing them to market for years. These graduates had an uncanny ability to visualize products in the final application and judge how they would perform. They quickly became integrated and valuable contributors to our team, months to years ahead of our expectations. Once we experienced the quality of these graduates, we hired as many as we could. At one time we had hired all but one of the fourteen Ph.D. students; we would have hired that one too, if there had been an opening. Unfortunately, one of our competitors hired this individual.

Years later, these graduates are still breaking new ground and raising the bar for others. They are establishing incubators in New York and computer modeling centers in California, running clinical study departments, managing product development for Fortune 500 companies, starting new companies, and providing leadership in many notable organizations. Most significantly, some of them are teaching, and all of them are both teachers and students. That is because Dr. Iaizzo ingrained in them the value and importance of continual learning and passing on knowledge to others. As a result, they are collaborators by nature, and they make a difference.

Finally, I have to give credit to Dr. Iaizzo and his academic partners for the role they played in creating a new environment between the University of Minnesota and the medical device industry. Their response to the educational needs of the industry over the past 20 years has been more than notable—it is remarkable!!

My experience with this dynamic group started with a casual comment made to Dr. Iaizzo in a hallway conversation almost 20 years ago regarding the need for training of industry scientists and engineers on anatomy and physiology. That hallway conversation sparked the annual “Advanced Cardiac Physiology and Anatomy” course, creating what has become the gold standard for training on the basics of anatomy and physiology for medical device professionals. Additionally, Dr. Iaizzo participates in the “New Product Design and Business Development” course, which was developed to pair business people with students to work in partnership with companies to solve real-world new product issues. Importantly, he created the Visible Heart Lab which represents the first major collaborative breakthrough in several years that initiated a change in the dynamic between the industry and the University. Subsequently, the University approved the establishment of the Medical Devices Center that has broken new ground in working in close partnering relationships with the industry. Building upon such work, the team of Professors Art Erdman, Will Durfee, and Paul Iaizzo founded the Design of Medical Devices Conference that is already a large and globally recognized annual conference. Last year the University announced a new policy governing intellectual property, which makes it easier for companies to license technology and enhances the University’s ability to capitalize on its research. This year a master’s degree in medical devices was offered for the first time. For years the University of Minnesota and the device industry did not partner well. Today they have set the standard for what collaborations between industry and academia can be, and it gets better every year.

I am amazed and in admiration of what a team of creative people can do when they decide to do what most think is impossible. Enjoy the book; it gives you a sense of the quality of the people involved.

LifeScience Alley and the BioBusiness Alliance of Minnesota  
Minneapolis, MN, USA

Dale Wahlstrom

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## Preface

Personalized medicine, clinical imaging, and the medical device industry continue to grow at an incredibly rapid pace. Further, our overall understanding of the molecular basis of diseases steadily increases, as does the number of available therapies to treat specific health problems. This remains particularly true in the field of cardiovascular care. With this rapid growth rate in cardiac medicine, clinicians and biomedical engineers alike have been challenged to either retool or continue to seek out sources of concise information.

The major impetus for this third edition was to update this resource textbook for interested students, residents, clinicians, and/or practicing biomedical engineers. A secondary motivation was to promote the expertise, past and present, in the areas of cardiovascular science at the University of Minnesota. As Director of Education for the Lillehei Heart Institute and Associate Director for Education of the Institute for Engineering in Medicine at the University of Minnesota, I feel that this book also represents a unique outreach opportunity to carry on the legacy of Drs. C. Walton Lillehei, M.D., Ph.D., and Earl Bakken, M.D., Ph.D. (Hon.) through the twenty-first century. Interestingly, the completion of this textbook coincides with two recent important anniversaries in cardiovascular medicine and engineering at the University of Minnesota. First, it was 61 years ago, in 1954, that Dr. C. Walton Lillehei performed the first cross-circulation procedures at the University. One year ago in January, Earl Bakken (the cofounder of Medtronic) turned 90 years old; Dr. Bakken has five implanted Medtronic devices and continues to be an inspiration to those working in this field.

For the past 15 years, the University of Minnesota has presented the week-long short course *Advanced Cardiac Physiology and Anatomy*, which was designed specifically for the biomedical engineer working in the industry; this serves as the course textbook. Thus there was a need to update the textbook to include state-of-the-art information on a variety of topics related to cardiac anatomy, physiology, and devices. For example, six new chapters were added to this third edition, and all other chapters were carefully updated and/or greatly expanded. One last historical note that I feel is interesting to mention once again is that my current laboratory, where isolated heart studies are performed weekly (the Visible Heart<sup>®</sup> laboratory), is the same laboratory in which C. Walton Lillehei and his many esteemed colleagues conducted the majority of their cardiovascular research studies in the late 1950s and early 1960s. It is also the laboratory where Earl Bakken, along with Drs. Vincent Gott and Lillehei, first tested the wearable battery-powered pacemaker on an animal with an induced heart block. After being tested on an animal, the prototype pacemaker was very quickly (later the same day) used by Dr. Lillehei on one of his cardiac surgical patients.

With this new edition, complimentary materials (e.g., movies and images) that will enhance this textbook's utility can be accessed online. Additionally, my laboratory continues to support the online, free access website *The Atlas of Human Cardiac Anatomy* ([www.vhlab.umn.edu/atlas](http://www.vhlab.umn.edu/atlas)) which also contains many tutorials and unique movie clips of functional cardiac anatomy. These images were obtained from human hearts made available via LifeSource (St. Paul, MN, USA), through the generosity of families and individuals who made the final gift of organ donation for research (their hearts were not deemed viable for transplantation).

I would especially like to acknowledge the exceptional efforts of our Lab Coordinator, Monica Mahre, who for a third time (1) assisted me in coordinating the efforts of contributing authors, (2) skillfully incorporated my editorial changes, (3) verified the readability and formatting of each chapter, (4) pursued 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 Gary Williams for his computer expertise and assistance with numerous figures; Tinen Iles and Charles Soule who made sure the laboratory kept running smoothly while many of us were busy writing or editing; the Chairman of the Department of Surgery, Dr. David Rothenberger, for his support and encouragement; the Institute for Engineering in Medicine at the University of Minnesota, headed by Prof. Bin He, who helped support this project via educational funds; and the Lillehei Heart Institute at the University of Minnesota, headed by Dr. Daniel Garry, who also generously supported educational outreach efforts.

I would like to thank Medtronic, Inc., for their continued support of the Visible Heart® laboratory for the past 18 years, and I especially acknowledge the commitment, partnership, and friendship of Tim Laske, Mark Hjelle, Alex Hill, Michael Eggen, Nick Skadsberg, Mark Borash, Rick McVenes, and Dale Wahlstrom for making our collaborative research possible.

It is also my pleasure to thank the past and present graduate students or residents who have worked in my laboratory and who were contributors to this third edition including Sara Anderson, Michael Bateman, James Coles, Michael Eggen, Kevin Fitzgerald, Alexander Hill, Brian Howard, Stephen Howard, Tinen Iles, Jason Johnson, Ryan Lahm, Timothy Laske, Anna Legreid Dopp, Michael Loushin, Lars Mattison, Jason Quill, Maneesh Shrivastav, Daniel Sigg, Julianne Spencer, Eric Richardson, Nicholas Skadsberg, and Sarah Vieau. I feel extremely fortunate to have the opportunity to work with such a talented group of scientists and engineers, and I continue to learn a great deal from each of them.

Finally, I would like to thank my family and friends for their continued support of my career and their assistance over the years. Specifically, I would like to thank my wife, Marge; my three daughters, Maria, Jenna, and Hanna; my mom Irene; and my sisters Chris and Susan, for always being there for me. On a personal note, it has been a difficult couple of years as both of my brothers passed away, as well as my longtime laboratory scientist Bill Gallagher. Furthermore, I myself dealt with some health issues that provided me with a much greater appreciation for cardiac medicine, medical advances, and what it feels like to be a patient. I am truly inspired by all individuals who dedicate their lives to all aspects of cardiovascular science and technology.

Minneapolis, MN, USA

Paul A. Iaizzo

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