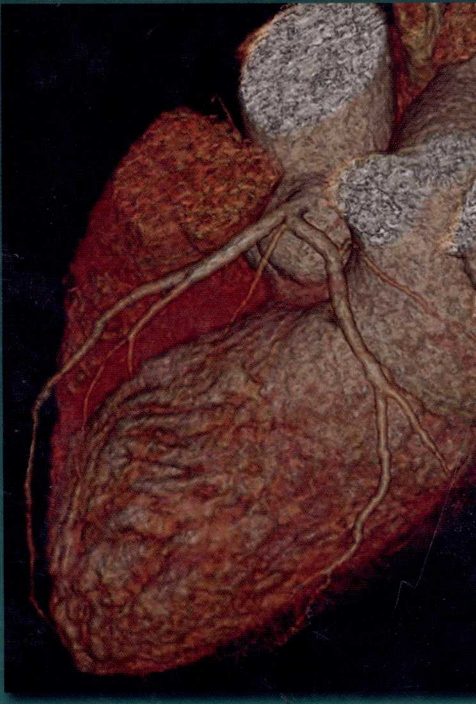
CT and MR ANGIOGRAPHY

Comprehensive Vascular Assessment



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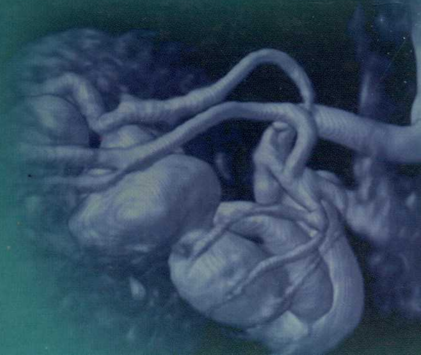

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CT and MR Angiography:

Comprehensive Vascular Assessment

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Dedication

To my wife, Rhesa, my strength and support, little of my accomplishments would be possible without you, to Rainier, Elka, Giulianna, Magellan, and Griffin, the best kids any Dad could hope for, you teach me new things everyday, and to my parents, Ann and Sheldon, who have enabled so many opportunities to become realities.

—GDR

To my wife, Lisa, for empowering and enriching my life, to my children, Anna and Bennett, who make everything worthwhile, and to my parents, Lorraine and David, for showing me that possibilities are infinite.

—NMR

Preface

Cardiovascular diseases represent the leading causes of death in the United States, Europe, and regions of Asia. Conventional angiography has played a dominant role in the diagnosis and characterization of these disorders using high-spatial and temporal resolution for luminal visualization of the cardiovascular system. However, even as a backbone for the evaluation of cardiovascular diseases, its fundamental limitations are noteworthy: each contrast injection typically provides a single perspective of often complex, three-dimensional vascular anatomy; there are geometric constraints that prevent access to many critical imaging perspectives; there is a restricted sensitivity to low contrast details in the anatomy; there is no ability to directly visualize the blood vessel walls and perivascular tissues; and its invasiveness has a substantial impact on both the patient and the cost of performing the diagnostic evaluation.

Due to innovations in hardware, software, and image analysis technology, computed tomography (CT) and magnetic resonance imaging (MR) angiography are now at the forefront of clinical cardiovascular imaging. In fact, these "noninvasive" techniques are replacing conventional angiography and are poised to serve as a new gold standard by providing equivalent or, in many cases, superior characterization of cardiovascular abnormalities. Both CT and MR are three-dimensional imaging tools that are built from thin section acquisitions, yielding volumetric data that can be assessed from innumerable perspectives, both graphical and quantitative. When combined with the advantages of eliminating the need for arterial punctures, a compelling case for the widespread adoption of noninvasive CV imaging with CT and MR emerges.

The rapid and continuous evolution of these tools for cardiovascular evaluations has left medical imaging practitioners in a challenging position. Many physicians with a deep knowledge of cardiovascular anatomy and disease need to master the skills in image acquisition and interpretation required from technologies that are fundamentally different from the traditional skill set required of conventional angiographers. Conversely, many sophisticated users of CT and MR technology may not have the requisite understanding of cardiovascular anatomy, disease, and treatment options. Thus, we intend for this book to fill the respective gaps that now exist and, in so doing, broaden the range of individuals capable of generating terrific images and delivering the key information for effective patient management. Furthermore, referring physicians will be afforded a resource to understand the capability of these modalities to provide the information they may be seeking.

We have been fortunate to have recruited top cardiovascular CT and MR experts to present an integrated approach to the acquisition and analysis of volumetric cardiovascular imaging. We have strived for a balanced and uniform approach supported by ample references. It is our sincere hope that readers find this work to be a staple of cardiovascular imaging and one that will be "well worn" from frequent use in daily practice.

Foreword

When I published the first edition of *Abrams' Angiography* almost a half century ago, the field of vascular imaging had advanced to a point at which a comprehensive reference volume was required. Over the next few decades, a new subspecialty was created based on catheter technologies that were moderately invasive and afforded exquisitely precise selective visualization of many branches of the central and peripheral vascular bed. Just as sophisticated imaging methods have invariably preceded surgical progress in the viscera—the brain, the gastrointestinal tract, the kidneys—so the improvements in vascular radiology underlay much of the progress in vascular surgery and the creation of the entire field of interventional radiology.

During the late 1950s and early 1960s, selective coronary arteriography was introduced and then was evermore widely applied to the study of the coronary circulation. The images were so striking that the arteriogram became the gold standard for confirmation of the presence of disease: the vessels involved, the degree of stenosis, the patency of by-pass grafts, and the congenital anomalies of clinical significance. In this setting, the diagnostic catheter was later converted into a therapeutic instrument, as balloon angioplasty became an important option.

Freeman Dyson, the great physicist at the Institute for Advanced Study (Princeton), has noted that concept-driven science has not always recognized or understood the cataclysmic contributions based on "tool" revolution. Just as the Galileo transformation in astronomy was based on the telescope, so x-ray crystallography radically changed biology. (Rosalind Franklin's images of DNA were the real foundation behind the Watson-Crick formulation of the structure of the DNA molecule.) The huge accumulation of knowledge of cardiovascular physiology and disease that characterized the 20th century was based far less on innovative research ideas than on the application of extraordinarily versatile tools, x-rays first and foremost. Side by side with the electrocardiogram, echocardiography, and the biochemistry laboratory these methods have afforded the clinician with a wealth of information critical to the management of patients with heart disease. Catheter angiography, however, has had its costs, monetary to be sure but also biologic. As an invasive procedure, it has well-known complications as well as contrast media reactions. It also involves exposure to ionizing radiation. Clearly, less-invasive methods would be desirable.

This brings us directly to the rationale behind this impressive volume. In the continuing search for methods that are safer and less consequential to patients, both MRI and multidetector CT have proven to be invaluable approaches to visualizing the heart and vascular bed. At such a point in the history of technologic advance applied to human subjects, an imperative become clear to fine minds in the field. The need becomes pressing to organize the huge amount of pertinent information that has become available. The lessons that have been learned, the variations in technique that have been developed, and the value of the methods in each vascular bed can all be embodied in a single volume to which both newcomers and those already in the field may refer. The challenge is very large, and it can only be surmounted when experience and expertise are coupled with unusual organizational ability, strong motivation, working weekends, and familiarity with the best sources in the field.

Drs. Rubin and Rofsky have risen to the challenge. With the help of their talented colleagues, they have produced a text that is thoroughly documented and profusely illustrated. While its practicality lends a strong "how to" quality to the volume, it responds equally well to the intellectual demands of the large literature which has been analyzed in each chapter.

In line with their hope and desire, *CT and MR Angiography* will be viewed as a seminal text for many years to come.

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With Special Thanks

Daniel Nóbrega Costa, MD
Editorial Assistance

Nancy Prendergast, MD and Kimberly Battista
Medical Illustrations

Acknowledgments

I am indebted to my mentors for being so giving of their time, their knowledge, and their enthusiasm for medical imaging. They have lead me to a truly rewarding career. As a medical student at UCSD, Skip vanSonnenberg's exuberant spirit helped me appreciate the power of imaging in medical diagnosis and therapeutic guidance and lead me to choose a career in radiology. As a resident, Brooke Jeffrey and Gary Glazer both showed me what it meant to be a CT master. I marveled at their insightful syntheses of keen observation and inference. The foundation for my career in academics and my deep affinity for cardiovascular imaging were created by Michael Dake. Starting a new clinical application as a third year resident was a challenge and without angiographic correlation all I had were pretty pictures. Mike saw to it that anyone in whom he found a stenosis, aneurysm or dissection came to me for CTA. The correlations and Mike's insights were critical; his creativity was an inspiration. Of equal importance to our nascent non-invasive CV imaging program, Sandy Napel exposed me to computer graphics and opened my mind to a wealth of possibility in volumetric image analysis. Our 17-year collaboration (and counting) has been the key to many imaging innovations. It also resulted in the creation of our 3D Laboratory. Lead by Laura Pierce, the tremendously talented staff has been critical to bringing the benefits of 3D applications to tens of thousands of Stanford patients and their physicians. The support, collegiality, and expertise of cardiothoracic and vascular surgeons, Scott Mitchell, Craig Miller, Neal Olcott, and Chris Zarins contributed greatly to the adoption and acceptance of CT angiography at Stanford and brought me opportunities to introduce CTA to a rich worldwide community of cardiovascular specialists.

I am grateful to my many colleagues in the Department of Radiology at Stanford. I wish that I could name you all. Without you I would not be spending my twentieth year in the department. Of equal importance to my contentment has been the energy and enthusiasm of the greatest students, residents, and fellows anywhere. I am particularly indebted to those former Stanford trainees who were invaluable in pulling this book together—Danny Donovan, Tamer El-Helw, Rich Hallett, Amir Pezeshkmehr, Justus Roos, and Pietro Sedati.

Finally a gigantic thank you to Neil Rofsky who has been a tremendous partner in this the most extensive and exhaustive of my academic efforts to date. Thank goodness for those late night jam sessions. What's next, a second edition or a rock opera about writing the first?

—GDR

There are so many individuals that I am indebted to for inspiration, for time and patience, for open mindedness, for intellectual generosity and for posing critical challenges—these gifts and the spirit behind them have allowed me to accomplish much more than I could have imagined possible.

The formative years for my MRA experience at NYU were an era of discovery, productivity, strong collaboration and immeasurable joy. The phenomenal team that included Glynn Johnson, Glenn Krinsky, Vivian Lee and Jeffrey Weinreb ensured our successes. Jeff deserves special recognition since it was his original suggestion that prompted me to pursue MRA, which ultimately changed the course of my professional career. That proposition was initially met with reluctance from me, a radiologist trained in abdominal imaging and fearful of being a fish out of water. But, thanks to the many hours and cases spent with vascular-interventionalist Bob Rosen, and with vascular surgeons, Mark Adelman, Gary Giangola, Pat Lamparello and Tom Riles, a solid foundation was established to launch the new path in my career. I have vivid memories of being the young, upstart radiologist in the NYU vascular surgery conference, always asking "what about MRA?" to which, in the early days, there would be responses of eye-rolling, shoulder shrugging and other physical demonstrations of doubt laced with contempt. This starkly contrasts against a more recent memory, at my very last NYU vascular surgery conference, when one of the vascular surgery attendings was laying into his resident asking, "what about an MRA?", incredulous that this option had not been considered.

Along the way and through a mutual interest in this "new field" I have met many exceptional people. It is with particular gratitude and fondness that I can recognize the gifts of knowledge, nuance and friendship that evolved from lectures, discussions and collaborations with Bob Edelman, Paul Finn, Tom Grist, Gerhard Laub, Chuck Mistretta and Martin Prince, during those early years and to the present day. I continue to learn from the ever growing number of experts in the field, a reflection of the successes and expansion of this important discipline. I am also grateful for the contributions of the technologists who ably implement our developments and the talents of our many students, whose thirst for knowledge insures that the future of our field will be one of boundless opportunity.

Geoff and I have tried our best to credit all those who have been kind enough to share case material—if by chance memory or process has fallen short and you recognize one of your images lacking recognition, please let us know so that we can ascribe the due credit in the (gulp) next edition!

—NMR

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IMAGING PRINCIPLES

PART

I

Principles of Computed Tomographic Angiography

CHAPTER 1

Mathias Prokop

Computed tomographic angiography (CTA) is one of the big success stories in diagnostic radiology. CTA was developed shortly after the introduction of spiral (helical) CT scanning in the early 1990s. Spiral CT had made it possible to cover body regions so rapidly that the transient enhancement of the vascular system following intravenous contrast injection could be captured during one scan. With the introduction of multidetector-row technology, CTA gained a tremendous boost and quickly became an easy-to-perform standard technique for vascular imaging.

Over the years, CTA—together with magnetic resonance angiography—has taken over most diagnostic vascular procedures from invasive catheter angiography, first for the aorta and the pulmonary arteries; later for the carotids, renal, and splanchnic arteries; and recently also for peripheral arteries and the circle of Willis. Most recently, CTA of the coronaries has been developed. While coronary CTA is still technically challenging, it also holds the promise to substitute for part of diagnostic cardiac catheter angiographies.

CTA has the advantage that it can be highly standardized, which makes it a very fast and robust procedure that is the technique of choice in many acute vascular diseases. It provides three-dimensional information with a comparatively high spatial resolution and allows for simultaneous evaluation of the vascular lumen as well as the vessel wall and the surrounding structures. In fact, every arterial phase CT can potentially serve as an arterial CTA, while a portal phase scan can serve as a portal venous CTA.