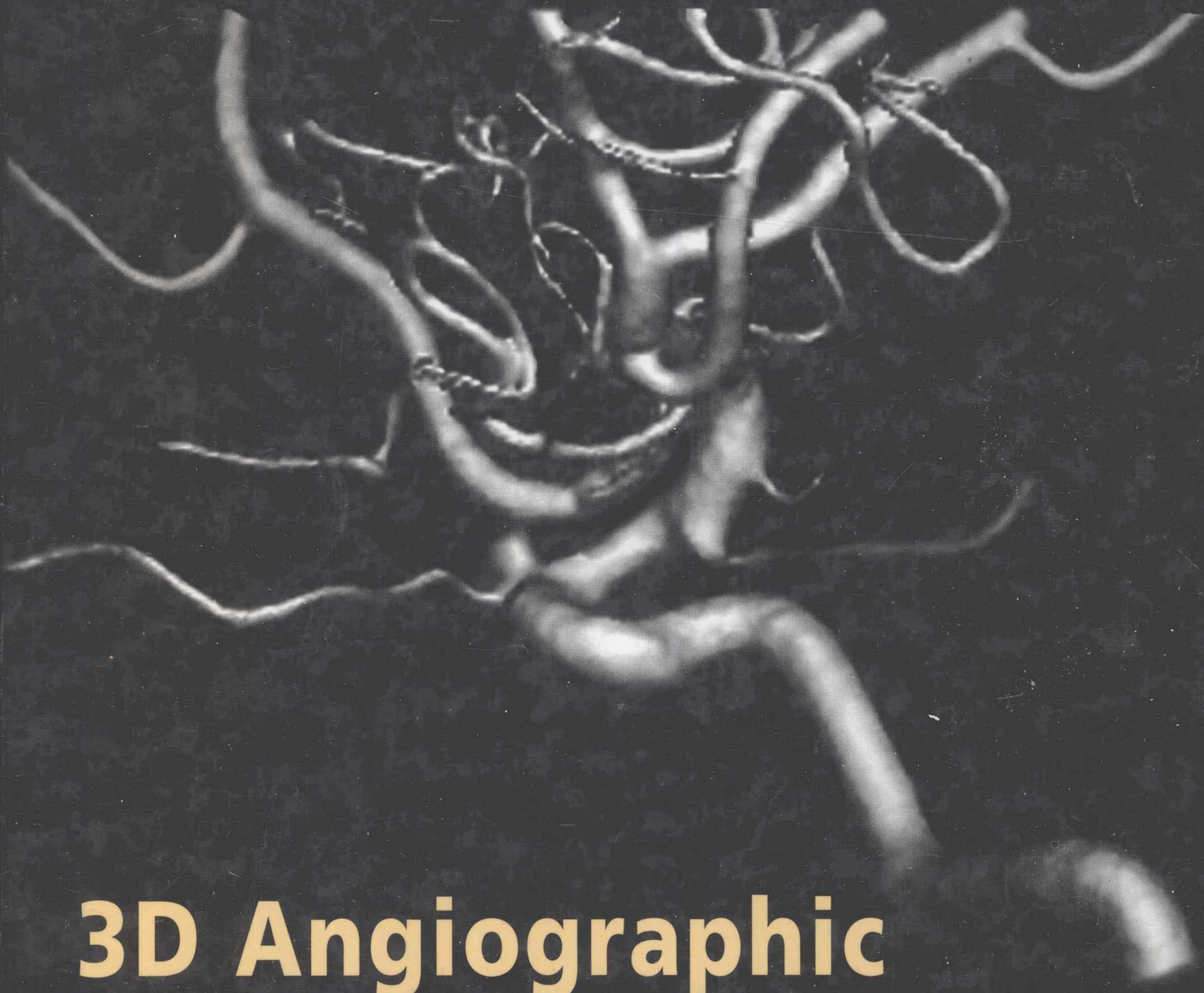
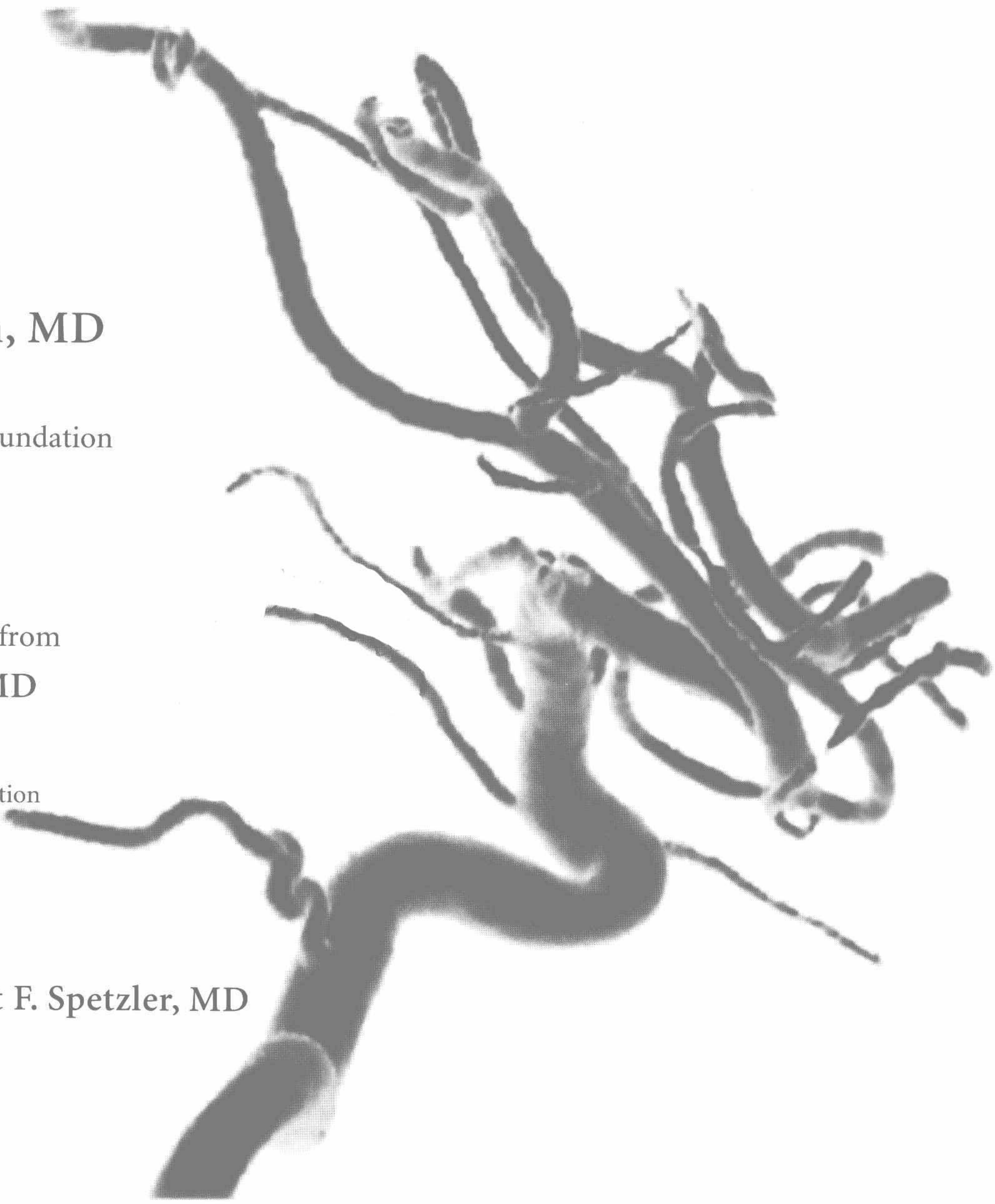


3D Angiographic Atlas of Neurovascular Anatomy and Pathology

NEIL M. BORDEN

With text contributions from Jay Costantini

3D ANGIOGRAPHIC ATLAS OF NEUROVASCULAR ANATOMY AND PATHOLOGY



Neil M. Borden, MD

Division of Radiology
The Cleveland Clinic Foundation
Cleveland, Ohio

With text contributions from

Jay K. Costantini, MD

Division of Radiology
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Cleveland, Ohio

Foreword by Robert F. Spetzler, MD

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FOREWORD

We have all – patients and physicians alike – come to take the capabilities of diagnostic imaging technology for granted; indeed, our expectations of that technology continue to increase – higher resolution, faster acquisition times, less artifact – the list of demands goes on and on. However, it is scarcely within the span of a generation that lesions considered occult in one imaging modality can now be diagnosed based on features that are pathognomonic in another modality. Young clinicians embarking on their careers at this time may be unaware, for example, that cerebral cavernous malformations with their distinctive appearance on magnetic resonance images were not that long ago considered to be angiographically occult arteriovenous malformations.

I offer this brief historical detail because readers of this volume are about to embark on an amazing three-dimensional visual journey of the circulation of the brain and neck that very few years ago would have been impossible. From the perspective of a neurosurgeon, the appreciation of the vascular system afforded by these images is priceless. Not only does three-dimensional rotational angiography improve the accuracy of diagnosis, it considerably enhances our ability to optimize treatment for patients with challenging neurovascular disorders. Preoperative planning is immeasurably improved by the ability to rotate these images in space to view the posterior regions of vessels that can even be difficult to view intraoperatively. The neck of an aneurysm, for example, can be assessed to determine its suitability for clipping or the presence of other vessels whose inclusion in a clip could be catastrophic. The experience is the neurosurgical equivalent of viewing the dark side of the moon – and always somewhat miraculous to those of us who trained when little more than conventional radiography and angiography were available. To note merely that patient outcomes are concomitantly improved is an understatement that fails to do justice to the lives that can be saved and the devastating complications that can be avoided.

The technology and images showcased in this volume also offer a huge educational benefit. Students, neurosurgical trainees in particular, have always had to struggle with translating the two-dimensional images of neurovascular anatomy in textbooks into the pulsating three-dimensional wonder of the human brain. The hundreds of beautiful images in this text will offer great solace to those striving to master this complex task. The color anatomical illustrations in Chapter 2 and the three-dimensional reconstructions in the orientation insets on each page help readers to place the three-dimensional angiographic images of the vasculature in their anatomical context. The liberal use of conventional angiographic images also helps readers to appreciate the normal anatomy and its perturbation by pathology.

That this superb angiographic atlas was assembled by Dr. Neil Borden is no surprise. Even as a resident Neil gained the reputation of being a "walking radiology encyclopedia" and a "sponge" for knowledge. Between 1994 and 1996, Neil completed a fellowship in interventional neuroradiology with us at the Barrow Neurological Institute in Phoenix. He joined us as a seasoned neuroradiologist who left an established practice to pursue additional training, and I believe that his choice to do so reflects his undiminished love of learning and teaching.

Remarkably, Neil had little experience in research or publishing when he joined us. His commitment and dedication to medical education are now manifest in the volume before you. Having assembled a few neurosurgical atlases during my career, I can assure readers that the finished product is the culmination of hundreds and hundreds of hours spent acquiring and weeding through countless images to optimize the learning process. The technology provides the images, it is true. However, only Neil's keen intellectual competency could have created this thoughtfully formatted and beautiful atlas. It is my pleasure and honor to recommend *3D Angiographic Atlas of Neurovascular Anatomy and Pathology* to both students and masters of the neurosciences.

Robert F. Spetzler, MD
Phoenix, Arizona

CONTENTS

INTRODUCTION

Over the last 8 years I have been archiving and cataloging angiographic images that I obtained using one of the first three-dimensional rotational angiographic systems. My career has allowed me to use angiographic cut film, two-dimensional digital subtraction angiography (2D DSA), and now three-dimensional rotational angiography (3DRA). This revolutionary angiographic technique maximizes diagnostic accuracy and provides an invaluable teaching tool for anyone interested in learning more about cerebral vascular anatomy.

The 3D representation of the human neurovascular system represents an enormous step forward in our ability to display this complex anatomy. Our goal in anatomical imaging is to try to recreate the in vivo status as close to its natural state as possible.

Until recently we have had to rely solely on 2D representation of this anatomy. Only recently have certain techniques emerged that can display the natural anatomic state in a 3D display. These techniques include 3D rotational catheter angiography, CT angiography (CTA), and magnetic resonance angiography.

There are three reasons why it is important to have the ability to view vascular anatomy in a 3D display. First, a 3D display is a more accurate representation of the pre-existing anatomy of the subject and can only improve our diagnostic accuracy. The evolution of imaging techniques over the last few decades has been aimed at achieving the most accurate reproduction of the anatomy and pathology possible.

The second reason for the importance of 3D display is a natural extension of the first reason. Only through analysis of the true/real anatomic composition of our subject can we make the most appropriate recommendations regarding prognosis and potential interventions (conservative management, traditional surgery, and/or endovascular surgery).

Any technique that converts and illustrates a 3D object as a 2D representation must involve the loss of certain data that can limit the accuracy of this transformation. This limitation in the representation of vascular anatomy can result in diagnostic inaccuracies and errors in interpretation that can ultimately lead to errors of judgment in therapeutic decisions. Ultimately, patient care can be negatively impacted by traditional 2D imaging methods that do not provide a 3D display of the anatomy.

The third advantage of displaying anatomy in a 3D format involves the education of individuals interested in learning this complex anatomy. This is of great importance to the authors of this book.

Excellent edge resolution can be achieved with both cut film and 2D DSA. However, these techniques lack the ability to provide critical information regarding the dimension of depth. Why is the ability to render depth so important? The cerebral vascular tree is tortuous and inconstant. Vessels often overlap each other. The relationship of one vessel to another provides critical data for operative/endovascular planning and execution.

3DRA has become a valuable tool in assessing the morphology of intracranial aneurysms. The neck of an aneurysm can be more precisely assessed with this technique. In addition, the takeoff of vascular branches and their relationship to the neck and walls of the aneurysm are data that can mean the difference between an easily treatable aneurysm to one that carries a higher risk for the patient. This information is important to have prior to any intervention.

3DRA is unlike any other technique because it allows for an unobtrusive view of the posterior wall of the vessel. This ability improves diagnostic accuracy and ultimately will improve patient care. Pathology does not limit itself to the anterior or lateral regions of a blood vessel. It is the angiographic technique (prior to 3DRA) which has limited assessment of posterior wall abnormalities. With certain steep oblique radiographic projections it might be possible to see certain regions of the posterior/postero-lateral walls of the vessel with high-resolution DSA. In most cases, optimum assessment of the posterior regions is not achievable. This region is easily assessed with 3DRA. In most cases, even direct observation during operative procedures does not allow adequate visualization of the cerebral vasculature.

Interventional neuroradiology has advanced rapidly in a short time. Microcatheter technology allows us to navigate throughout much of the cerebral vascular tree. Vessel relationships and morphologic detail provided by 3DRA can be critical information to those entering the complexity of the human cerebral vascular system. This knowledge can make these procedures safer for the patient.

This technique also enhances preoperative surgical planning. In my practice, the vascular neurosurgeon investigates the 3D image with me in real time at a computer workstation prior to taking patients to the operating room. The ability to observe the vessels in 3D prior to an operative intervention reduces any unwanted surprises at the time of surgery.

One of the limitations of 3DRA is its inability to demonstrate the smaller branches of the vascular tree. The larger proximal vascular trunks and medium-sized vessels are routinely observed and included when possible in this atlas. In my practice, 3DRA has been primarily used in the assessment of the arterial circulation with the only exception being lesions with arterial-venous shunts. Routine utilization of this technique for examining the venous circulation has not been performed except in unusual cases. Another limitation of 3DRA is the lack of visibility of background anatomy that provide spatial references.

This atlas contains images that demonstrate both normal vascular anatomy as well as different pathological entities. The text describes in broad strokes the most commonly encountered patterns of the arterial vascular tree both in the neck and intracranially. We cover the most frequently encountered vessels but leave detailed discussions of the different variations and functional neuroanatomical considerations to other textbooks in this field. We also touch on the subject of the intracranial venous system in more limited fashion as we have used 3DRA only in rare instances to image the venous circulation. 3D examples are supplemented with 2D images where appropriate to further enhance the utility of the atlas.

This book is intended to be a reference atlas of neurovascular anatomy (cervical and intracranial) and pathology. It is not intended to be a primer on the technique of generating 3D images. We have written this atlas with the intention of enhancing your ability to understand complex neurovascular anatomy. It is our expectation that the knowledge you take from this work will aid in your understanding of neurovascular anatomy in whatever imaging modality or clinical application you choose.

Neil M. Borden, MD

CHAPTER ONE

TECHNIQUE OF THREE-DIMENSIONAL (3D) ROTATIONAL ANGIOGRAPHY

Angiography is the study of blood vessels. Conventional catheter angiography is a technique that involves the injection of a positive contrast agent directly into the blood vessels through an indwelling vascular catheter (long thin hollow tube). These catheters are generally inserted percutaneously (via needles inserted through the skin).

Cerebral angiography using catheter technology involves accessing the arterial tree most often from the femoral artery (groin). Occasionally the brachial or axillary arteries may be used as the access point.

After the catheter is inserted into the desired arterial access point it is navigated into the vascular territory of interest. In cerebral angiography the catheters are most often placed into the cervical (neck) common carotid artery, internal carotid artery, external carotid artery, or vertebral artery. When nonselective injections are desired the catheters may be positioned in the innominate artery, subclavian artery, or even the aortic arch.

Once the catheter is in the desired position, a bolus injection of a positive contrast agent is performed during which X-rays are obtained for varying periods of time. This allows one to obtain images of the contrast agent as it progresses through the vascular tree from artery to capillary and then into the venous phase of circulation. Most often, the X-rays are obtained in fixed position. Different views of the blood vessels of interest can be obtained either by moving the patient relative to the X-ray tube or changing the position of the X-ray tube relative to a stationary subject. This is the basis for two-dimensional (2D) angiography.

The technique of three-dimensional rotational angiography (3DRA) occurs during the bolus injection of the positive contrast into the vascular tree when a movable X-ray tube rotates in an arc around the patient during acquisition of the X-rays. The X-ray data obtained from this series of exposures is sent to a computer workstation which then creates a 3D model of the vessels studied. This 3D model can then be manipulated on the workstation in real-time to provide an infinite number of projections (views) of the vessels imaged.

The technique of 3DRA will vary depending upon the manufacturer of the X-ray hardware and software. The author's experience, and all of the 3D images included in this atlas, were acquired using General Electric (GE) LCN+ equipment with a Sun workstation.

The X-ray c-arm (floor mounted X-ray tube and image intensifier) rotates in an arc of approximately 220 degrees around the patient during the injection of a contrast agent bolus. The speed of rotation of the GE equipment was 40 degrees per second. The entire arc of rotation during which data acquisition occurred would take approximately 5 seconds. It acquires approximately 8.8 frames (X-rays) per second generating approximately 44 images in a 512 × 512 matrix over that 5-second timeframe.

During setup for the 3D data acquisition, the region of interest would be placed in the isocenter of the image under fluoroscopy. The blood vessels of interest need to be in the center of the X-ray image in the frontal (AP) and lateral (from the side) projections. This would ensure that X-ray data from all projections would be included in the final 3D model that is generated. If the region of interest were to be placed at the edge of the X-ray field and was not included in the entire rotation, then the final 3D image would not include this partially imaged segment.

The next step after placing the subject in the center of the X-ray image would be to perform a test rotation. This is critical to ensure that there would be no physical collisions between the large, rotating c-arm and any nearby structures. This is especially important when dealing with interventional neuroradiology procedures requiring anesthesia equipment, arterial and other lines, ventilator equipment, and sometimes a ventricular drainage catheter setup. If a test rotation is not done then inadvertent removal of life supporting lines and equipment might occur if there was a collision or if one of the lines were to become tangled with the rotating c-arm gantry.

The technique of 3DRA utilizes a single bolus injection of contrast. As opposed to standard 2D angiography where the contrast bolus is visualized as it progresses through the vascular tree, the goal of imaging with 3DRA is to obtain all of the X-ray images in the same phase of circulation. Most often the arterial phase is desired, although this can be altered so that the venous phase can be the predominant portion of the vascular bed imaged. Since the image data is acquired over a 5-second time period during the arc of rotation, the goal of the injection is to opacify the desired vessels during the entire 5 seconds. Through experience we found that in most cases adequate opacification could be accomplished with approximately 15 cc total volume injected at a rate of 3 cc per second. These numbers could be modified depending on the size of the vessel where the catheter was residing, the cardiac output, and whether we were trying to image a high-flow state such as an arterial-venous malformation (AVM). We did not have a single complication related to these injection volumes over a 4-year period.

The operator/physician chooses a delay time to begin the rotational sequence after initiating the contrast injection. When the arterial circulation is the desired phase of circulation to be imaged, the delay is usually between 0.5 and 2 seconds depending upon the position of the catheter tip relative to the vessels of interest and the patient's cardiac output. The closer the catheter tip is to the area of interest the shorter the needed delay. When patients have impaired cardiac function, a longer time delay may be required to allow time for the injected contrast to reach the area of interest. Again, the goal is complete opacification of the vasculature of interest for the entire rotational sequence (about 5 seconds). Occasionally, when the venous circulation is the region of interest, much longer delay times are used. This can be estimated by evaluating the timing of the appearance of the veins on prior 2D angiographic sequences.

Once the rotational sequence is completed, the data is transferred to the Sun workstation where a 3D model is generated. With a 3D model available the operator/physician applies a threshold and utilizes other 3D tools to generate the final 3D image.

A variety of reconstruction algorithms are available which include shaded surface display (SSD), maximum intensity projection (MIP), volume rendering (VR), and a navigator view which allows for an endoluminal view of the vessels in the 3D volume set.

Most of the 3D images in this atlas are shaded surface display 3D images. This algorithm simulates a light source projected on the model, which generates varying shades of gray that enhance the 3D perspective.

After several software updates, a program was developed which allowed reconstruction of surgical clips and endovascular coils in the 3D image. When possible, I include some of these images in the atlas.

As stated in the "Introduction", there are certain limitations inherent with 3DRA technique. Visualization of small/distal vessels is limited. This limitation is partly related to the lower injection rate used compared with standard two-dimensional digital subtraction angiography (2D DSA). A second limitation is the lack of bony landmarks on the final 3D image. A third limitation is the lack of sequential visualization of angiographic images showing the progression of contrast through the various phases of circulation. For this reason 3DRA should not replace traditional high resolution 2D DSA, but should complement the angiographic examination.

CHAPTER TWO

COLOR ILLUSTRATIONS OF NORMAL NEUROVASCULAR ANATOMY