Cerebrovascular
Cerebrovascular Ultrasound in Stroke Prevention and Treatment

EDITED BY

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SECOND EDITION
# Contents

List of Contributors, iv  
Preface, vi  
Foreword, viii  
Preface to the First Edition, ix  
Foreword to the First Edition, x  
Acknowledgment (First Edition), xii  
Practice of Ultrasound: an Introduction, xiii  

## Part I  How to Perform Ultrasound Tests, 1

1 Principles of Extracranial Ultrasound Examination, 3  
Andrei V. Alexandrov, Alice Robinson-Vaughn, Clotilde Balucani & Marsha M. Neumyer  

2 Intracranial Cerebrovascular Ultrasound Examination Techniques, 13  
Andrei V. Alexandrov, Marta Rubiera, Paola Palazzo & Marsha M. Neumyer  

3 Anatomy of the Brain’s Arterial Supply, 26  
Joel Cure  

## Part II  Hemodynamic Principles, 45

4 Integrated Assessment of Systemic and Intracranial Hemodynamics, 47  
Anne W. Alexandrov  

5 Practical Models of Cerebral Hemodynamics and Waveform Recognition, 68  
Andrei V. Alexandrov  

## Part III  Criteria for Interpretation, 85

6 Diagnostic Criteria for Cerebrovascular Ultrasound, 87  
Georgios Tsivgoulis, Marsha M. Neumyer & Andrei V. Alexandrov  

## Part IV  Ultrasound in Stroke Prevention and Treatment, 145

7 Ultrasound in Stroke Prevention: TCD and Sickle Cell Disease, 147  
Fenwick T. Nichols III, Robert J. Adams & Anne M. Jones  

8 Cardiovascular Risk Factors and Carotid Ultrasound, 158  
Tatjana Rundek & Joseph F. Polak  

9 Applications of Functional Transcranial Doppler (fTCD), 177  
Konstantinos Vakakis & Georgios Tsivgoulis  

10 Transcranial Doppler in the Detection and Quantitation of Patent Foramen Ovale and Other Right-to-Left Circulatory Shunts, 187  
Annabelle Lao, Cindy J. Fuller & All T. Jeantur  

11 Ultrasound in Neurocritical Care, 198  
Andrew D. Barreto & James C. Crotta  

12 Cerebral Vasospasm after Subarachnoid Hemorrhage, 207  
Mark B. Harrigan, David W. Newell & Andrei V. Alexandrov  

13 Intra-Operative TCD Monitoring, 214  
Zei Garmi & Alan B. Lumadue  

14 Intracranial Stenosis, 228  
Vijay K. Sharma & K.S. Lawrence Wong  

15 Ultrasound in Acute Stroke: Diagnosis, Reversed Robin Hood Syndrome and Sonothrombolysis, 240  
Andrei V. Alexandrov, Robert Mikulik & Andrew Dimchuk  

16 Ultrasound and Gaseous Microspheres, 252  
Flamming Forsberg & Andrei V. Alexandrov  

17 Neurosonology Pearls, 262  
Georgios Tsivgoulis, Clotilde Balucani & Vijay K. Sharma  

Index, 275
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Preface

This edition was prepared during challenging times in my career. I took on the leadership position to organize the acute stroke care team at the University of Alabama Hospital, the home of Tinsley Harrison's internal medicine and Champ Lyons' surgery heritage, that is located in the buckle of the Stroke Belt of the United States. A number of accomplished physicians and scientists paid their dues in fighting this disease in Alabama prior to my arrival at UAB. The list (by no means complete) includes James Halsey, J. Garber Galbraith, Leland Clark, James Morawetz, Winfield Fisher, Gary Roubin, Dennis Doblar, Vijay Mista, Georg Deutsch, Camilo Gomez, Rodney Soto, Sean Orr, Joseph Horton, Michelle Robin, Edward Faught and Robert Slaughter. Dr Ray Watts, Chairman of the Department of Neurology, with the help of Drs Halsey, Rebecca Sugg and Andrew Barreto, recruited me and my wife, Anne Alexandrov, to UAB in 2007.

Our goal was to build a Stroke Team standing up to a meaning of the words – Comprehensive Stroke Center. We started with education at multiple levels of health professionals about a proactive, "reasons to treat" approach to stroke, removing the word "diversion" from stroke patients access to UAB, instituting shared stroke assessment, treatment and prevention protocols across all physicians on service, opening a dedicated universal-bed concept Stroke Unit and engaging multi-disciplinary care providers in this process.

Prior to start of "code stroke" in 2007, only four intravenous tPAs and just one intra-arterial thrombolysis procedure were given at UAB Hospital comprising less than 3% and 0.5%, respectively, of consecutive stroke patients being treated with reperfusion therapies. In 2008, these numbers were 38 (13%) and 20 (7%) and in 2009 we reached 100 (20%) and 40 (9%).

This could not have happened without our Team members who share the same "find reasons to treat" philosophy towards stroke care: stroke attendings Karen Allbright, Damon Patterson, John Brockington, John Rothrock; our interventionalists Damon Patterson, Mark Harrigan, Joseph Horton, Ed Underwood, Vijay Mista; our neurologists who help at multiple levels, Ivan Lopez, Jennifer deWolfe, Harrison Walker; our clinical and research fellows Aaron Anderson (winner of the 2009 Golden Plumber Award for the best Neurology Resident performance on Stroke service), Luis Cava (2010 Golden Plumber), Thang Huy Nguyen (who also contributed photographs to this edition with his remarkable camera skills), Marta Rubiera, Yi Zhang, Clotilde Baliscani, Paola Palazzo, Kristian Barnlin; our nurse practitioner and clinical trial coordinator Mary Brethour and April Sisson; our sonographers Alice Robinson-Vaughn, Limin Zhao; and our Stroke Center staff who try to keep up with all of us: Alexis Jernigan and Sarah Bullock.

A special thanks to Georgios Tsivgoulis, a superb stroke neurologist and sonographer who bravely followed me to Alabama, helped us start this process and continues to conduct very productive research with us and our gurus in biostatistics/epidemiology George and Virginia Howard; and to Anne Alexandrov who coordinates multiple clinical and research protocol developments, education of staff and for her pivotal role in creation of the universal-bed Stroke Unit.

Our Team includes all nurses: first on M8 under the leadership of Elizabeth Toohey and Beth Clarkson and now on the Stroke Unit under Kathy Langley, Jill Stewart and Velinda Block, who offered tremendous support to innovations in care and research being delivered in this Unit.

Other members of our Stroke Team include all of the University Emergency Medicine faculty physicians, residents and nurses among whom I particularly would like to mention Janyce Sanford, Sarah Nahzig, Christopher Rosco, Henry Wang and Andy Thomas for their continuing support and fighting many political battles for us; Neurosurgery Department faculty physicians, residents and the Neuro-Intensive Care Unit staff with particular acknowledgement of vascular neurosurgeons Winfield Fisher and Mark Harrigan; Neuro-Radiologists Glenn Roberson, Joseph Horton, Joseph Sullivan, Robert Chapman and Joel "The Oracle" Cure; the Neuro-Vascular Laboratory staff at the
Preface

UAB Heart and Vascular Center; Vascular Surgeons under the leadership of Will Jordan; Neuro-Rehabilitation specialists Eugene Taub, Victor Mark and Bill Baker; Palliative Care Team staff and physicians Heather Herrington and Rodney Tucker; and of course the backbone of Stroke service – all our current Neurology Residents and graduates among whom I particularly would like to mention Andrew Barreto (now at UT-Houston, with whom we continue close collaboration), Bijay Pandy (2008 Golden Plumber), Tiffany Pineda (2009 Golden Plumber runner-up, for “No Ear-Plugs Needed” resident performance on stroke service), Victor Sung (2009 Golden Plumber runner-up) and Hayden Countryman Long (2010 Golden Plumber runner-up). Their endless efforts on the most difficult clinical rotation made a huge difference in many patient lives.

Andrei V. Alexandrov, MD, RVT
Birmingham, AL
Foreword

Neurosonology – dead or alive?

Alive and Kicking!

With the advent of modern imaging technologies and non-invasive assessment of extra- and intracranial brain vessels by both CT angiography and MR angiography, some clinical neuroscientists feel that this may initiate the end of the decades of neurosonology. Is this true or a misconception?

Back in the old days, more than 35 years ago, neurologists in Europe applied continuous wave sonography to explore cervical vessels, mostly the common carotid, the carotid bifurcation and the internal and external branches. Few even tried to insonate the vertebrae. With more and more advanced ultrasound technology, despite the major investments in CT imaging and, later on, MRI imaging, both pulse transcranial and B-mode-neurosonology were developed.

Of note, European neurologists, mostly in Scandinavia, Germany, Austria and Switzerland, made neurosonology part of the basic diagnostic techniques that neurologists offer, on the same level as EEG, EMG or evoked potential testing. Certification for physicians and, some time later, also for technicians was introduced. Basically, at the end of their 5-year training period, virtually every neurology resident in Germany will be an experienced neurosonologist, many of them certified by the National Ultrasound in Medicine Society.

In contrast, in North America, neurosonology was largely considered to be a technician’s area of expertise, with physicians only interpreting the results and putting them in perspective. Only in a few centers, such as Seattle and Houston, did academic neurosonography create their own school of physicians trained in ultrasound and applying this technique to their patients. This may, in the future, become more popular.

Sonography is not the tool for the one time assessment of the brain-supplying arteries and the intracranial vessels. This can be done more reliably with CTA and MRA. Neurosonology is a monitoring instrument which allows repetitive assessments without side effects and exposure to radiation during procedures such as in re-ccanalization therapies, in patients with dissections or floating thrombi or, with additional ultrasound contrast, in the monitoring of embolicigenic conditions. Furthermore, there may be hope for a therapeutic application of ultrasound. First steps in that direction have been made, and more steps will follow. Finally, three- and four-dimensional techniques and evaluations may help with individualizing treatment decisions, when it comes to the description of plaque morphology and differentiating “hot” plaques from “resting” plaques.

In Europe, several textbooks on neurosonology are available, many of them in their 3rd or 4th edition. This 2nd edition of the book by Andrei Alexandrov and co-workers represents a valid and profound counterbalance to European neurosonology, putting the techniques and future applications into perspective and setting the case for a more physician-applied neurosonology. The book is balanced and comprehensive and therefore could become the standard neurosonology volume for North America. Maybe at some point in time, a joint neurosonology textbook with contributors from North America, Europe and also Asia will follow.

Werner Hacke, MD, PhD
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February 2010
Preface to the First Edition

This book is about vascular examination of patients suffering from stroke and relevance of this information to treatment decisions. This book is for clinicians who are eager to learn, prepared to observe and would not stop explorations.

Ultrasound sharpens clinician’s ear and provides a stethoscope, an observation tool. And, like a microscope, an ultrasound probe needs a scientist to point it in the right direction. However, to paint a global picture, a complex ultrasound system also needs an artist to bring the art and science of medicine together. Ultrasound enables to monitor the cardiovascular system and brain responses to treatment in real time, a blessing on the way to develop stroke therapies and a handy tool to tailor treatment when the current evidence is meager.

I indebted to my friends and colleagues who spent countless time sharing their expertise in this book. Working with a Stroke Treatment Team is a thrill and this book is the result of many observations, often at obscene hours, that made us believe that stroke is treatable.

Andrei V. Alexandrov, MD
2004, Houston, TX
Foreword to the First Edition

Ultrasound: What's in the Waveforms?

The greatest advances in understanding and treating stroke have occurred in the past 30 years. This progress has coexisted with and largely resulted from our dramatically improved ability to diagnose stroke and its subtypes, characterize its location and severity and understand its causes rapidly, accurately and in real time. This has taken some of the charm out of clinical stroke care as the senior readers of this book will still remember even the most astute clinicians’ conclusions based on a careful history and physical exam proven wrong at the post mortem table. But the positive benefits of technology and improved diagnostic capability far exceed our nostalgia for the “good old days” when we relied mainly on our clinical acumen. What constitutes our improved ability to diagnose stroke? Unlike many other diseases, precise diagnosis of stroke depends almost entirely on imaging.

Our diagnostic capability took its greatest leap forward with the development of brain imaging, first with X-ray computed tomography and more recently with magnetic resonance imaging. Brain imaging has enabled us to quickly and accurately differentiate between infarct and hemorrhage, determine the location and surmise the probable cause and establish the age and severity of most strokes rapidly and painlessly. Brain imaging is now the first step in stroke diagnosis and treatment and has been called the “EKG of stroke.” This technology is now available in the vast majority of hospitals in the developed world and, more than any other component of our clinical management, distinguishes 21st century stroke care.

Physiologic imaging developed almost concomitantly with structural brain imaging. Our ability to investigate cerebral blood flow and metabolism using radio-labeled tracers enabled us to see that acute and chronic stroke is a dynamic and potentially reversible process that would eventually yield to timely and precise therapeutic intervention. Pioneering studies using xenon and positron emitting isotopes demonstrated reduced cerebral blood flow distal to chronic extracranial and intracranial occlusion or vasospasm, and, most importantly, revealed the “ischemic penumbra” of reversibly damaged brain tissue in acute stroke patients that has yielded so far to timely reperfusion and, at least experimentally, to so called “neuroprotective” therapies targeting downstream consequences of interrupted blood flow. Furthermore, the linkage of cerebral blood flow and metabolism discovered with physiologic imaging has generated our ability to carry out “functional imaging.” This technology is not only helping us understand the functional anatomy of simple and complex behaviors, but has also given visible proof of the plasticity of brain function. This has given a huge boost to research into treatment aimed at amplifying stroke recovery.

Imaging the vascular bed is the third critical aspect of stroke diagnosis. The seductive complexity of the brain draws our attention, but the stroke clinician must never lose sight of the fact that stroke is first and foremost a disease of the blood vessels nourishing that organ. Vascular imaging has been available to clinicians longer than our ability to image the brain parenchyma. Catheter arteriography can reveal the anatomy of extracranial and intracranial occlusive disease, aneurysms and arterio-venous malformations and for decades has been a standard part of the pre-operative evaluation of patients with severe forms of these conditions. However, it was not until the advent of “non-invasive” techniques, using ultrasound and more recently magnetic resonance and CT-angiography, that vascular imaging has become part of the routine evaluation of all stroke patients. Such testing has become critical to answer essential clinical questions that impact management of every stroke patient such as the cause of bleeding in patients with intracranial hemorrhage and the precise location, nature and severity of arterial occlusion or narrowing in patients with transient ischemic attack or ischemic stroke.

The advantages of ultrasound for vascular diagnosis are well known. It is a fast, portable, non-invasive, repeatable and inexpensive technique. The application of ultrasound to clinical stroke care over the past decades has revealed a number of clinical determinations that are best made by this technique and that directly impact on clinical decision-making. Among various clinical situations, the most established ones include:
the early detection and characterization of extracranial atherosclerosis and occlusive disease especially at the carotid bifurcation,
• the consequences of proximal arterial occlusive disease on the distal cerebral vasculature,
• the natural history and response to treatment of acute arterial occlusion that causes hyperacute stroke,
• the detection of microemboli associated with cardiac and aortic pathology and carotid artery surgical manipulation (and perhaps gauging response to anti-platelet therapy),
• selection of children with sickle cell disease for blood transfusion as an effective tool in primary stroke prevention,
• the time course and reversibility of cerebral vasospasm after subarachnoid hemorrhage.

Portable ultrasound machines and handy monitoring sets made it possible to bring this technology to bedside and observe remarkable flow changes in stroke patients in real time. However, the field of ultrasonic diagnosis also has its detractors and limitations. For many applications, ultrasound has not been thoroughly tested for its utility, accuracy and validity in multi-center studies. While the benefits of using this methodology for the above indications, as well as for others that undoubtedly will emerge as our exploration of stroke disease continues, may seem self-evident to those of us who live with ultrasound technology and use it every day, this is not so evident to others. Careful outcomes research investigating the accuracy and cost benefit of ultrasound is needed to establish the utility of this technique for any clinical situation where we surmise that it should be routine. Many such studies have been carried out and have established the value of ultrasound particularly for the clinical issues listed above. This book should help identify where such data exist, and more importantly, where more data is still needed.

Finally, early ultrasound technology was indirect, had poor resolution and had high rates of false positive and false negative results. Even now, the technique is “operator dependent” in terms of the accuracy and validity of its results. While, in fact, to some extent these concerns are true of all diagnostic imaging, these limitations have been particularly true of ultrasound. Newer technology has provided significant advances in this regard, but it is necessary for each and every laboratory to maintain strict quality control in order to maximize the information that this powerful technology can provide. This textbook provides a major advance in that regard. Written by experts in the field, it will provide sonographers with the tools needed to enhance the confidence of clinicians in utilizing ultrasound technology and the clinicians with additional information how to implement this technology in their everyday decision-making.

James C. Grotta, MD
2004, Houston, TX
Acknowledgment (First Edition)

I joined the University of Texas Stroke Treatment Team in 1996 and never regret the loss of life style or many sleepless nights. The best experience one can get is to work together with Team members who would race day or night to see and treat acute stroke patients breaking all speed limits and meeting any strict time windows. With countless hours spent together in the emergency department, angiography rooms, specialized care units and late night diners we shared thoughts and debated various ways to treat acute cerebral ischemia.

These observations would never have happened without Jim Grotta, a visionary for stroke treatment, who started this Team long before I joined it. He has led us to the highest percentage of consecutive stroke patients being treated with thrombolytics to date. This work would have never been accomplished without those who made it happen in Houston, current and former Team members, many of whom are now heading their own Stroke Teams in the United States, Canada and other countries (I apologize for not listing many more Stroke Team members who worked hard in Houston prior to 1996): Fahmi Al-Senani, Scott Burgin, Alex Brunser, Sergio Calleja, Morgan Campbell, Chin-I Chen, Oleg Chernyshev, David Chiu, Ioannis Christou, Andrew Demchuk, Ashraf El-Mitwalli, Robert Felberg, Zsolt Garami, Christiana Hall, Susan Hickenbottom, Yasuki Iguchi, Jennifer Ireland, Scott Kasner, Derk Krieger, Lise Labiche, Marc Malkoff, Robert Mikulik, Lewis Morgenstern, Elizabeth Noser, Nicholas Okon, Paisith Piriyawat, Marc Ribo, Hashim Shaltoni, Ken Uchino, Carlos Villar-Cordova, Teddy Wein and Frank Yatsu.

The words Stroke Treatment Team would remain just words without acknowledging everyday work of nurses, who took care of our patients and who carried out our pivotal as well as negative clinical trials. The Team is blessed with outstanding nurses who keep physicians on their toes: Patti Bratina, Sheila Ford, Dawn Matherne, Robin Saiki, Sandi Shaw, Dora Vital and Anne Wojner.

The Team could never be complete without interventionalists, cardiovascular surgeons, neurosurgeons, critical care, emergency physicians, scientists and proactive hospital nurse administrators who also made an enormous effort to be there on time and to brain-storm creative ways to combat the most resistive clinical and scientific problems: Jaroslaw Aronowski, Eddy Cacayourin, Linda Chi, Guy Clifton, Tony Eutreria, Tom Flanigan, Brent King, Dong Kim, Steve Koch, Bill Maggio, Joseph Nates, David Robinson, Hazim Saifi, Richard Smalling, Joon Song and Roger Strong.

This work would also have never been possible without Houston Fire Department, City Paramedics and many Emergency Room nurses, physicians and neurology residents.

2004, Houston, TX
Practice of Ultrasound: an Introduction

A variety of ultrasound tests have been introduced for the detection and monitoring of cerebrovascular disease in the past 50 years [1–10]. Advantages of ultrasound testing include its non-invasive nature, portability, real-time information and versatility. Imagine that one can sample tissues and flow behavior in real time at a rate of 5000 times per second. So far, no other imaging modality in wide use for stroke today comes close to this temporal resolution. Furthermore, ultrasound waves contain a mechanical pressure momentum resulting in energy transmission to tissues that in itself can yield a therapeutic effect.

Current and disappointing reality is that when a stroke patient gets an ultrasound evaluation, it is often limited to assessment of the extracranial portion of the carotid arteries, with an even more limited look at the vertebral arteries. Evaluation of brain vessels is reduced to a snapshot offered by a non-invasive angiography, if any. While in training, physicians dealing with stroke are not getting enough exposure to learning cerebral hemodynamics and the vastness of mechanisms of how strokes occur or can be reversed beyond the meager choice of approved therapies. This edition, in addition to the first, is intended to cover the gap for vascular neurologists to learn how ultrasound can enrich their ability to diagnose, evaluate and treat stroke and for sonographers to understand what information clinicians need from their tests. From the clinical applications standpoint, cerebrovascular ultrasound at present can:

1. Differentiate normal from diseased vessels and states,
2. Uncover plaques and identify the most dangerous ones,
3. Grade categories of stenosis in major pre-cerebral and intracranial vessels,
4. Localize the disease process including acute occlusions,
5. Detect progression of a variety of diseases, including cerebral circulatory arrest,
6. Detect, localize and quantify cerebral embolism,
7. Detect right-to-left shunts,
8. Assess the ability of collateral circulation to maintain cerebral blood flow or succumb to steal and
9. Monitor and even augment thrombolysis.

A single test procedure or a single transducer cannot yet accomplish all of these tasks. Sonographers have to learn how to use a combination of extracranial and intracranial tests and keep up with the progress in the field.

Prerequisites to a successful practice of cerebrovascular ultrasound include knowledge of anatomy, physiology of cardiovascular and nervous systems, fluid dynamics and pathological changes in a variety of cerebrovascular disorders [11–21] and also the basics of ultrasound physics and instrumentation [22–24]. No single textbook is sufficient in preparation for proficiency examinations, nor could it serve as a sole source of reference material in day-to-day practice. I use multiple sources and continue to learn from previously written texts (not limited indeed to the classic contributions referenced in this section) as well as continuing medical education conferences, research papers and presentations at numerous ultrasound and stroke-related meetings.

In the 6 years that have passed since the first edition of this book, I received multiple suggestions on how to improve it. Also, the aim of this second edition is to update the description of cerebrovascular ultrasound testing methods and criteria for interpretation and to illustrate how ultrasound provides information helpful in patient management.

The practice of ultrasound (both performance and interpretation) should be a mandatory part of the residency training for physicians of different specialties as well as the Vascular Neurology training pathway. It still remains problematic in the United States to have all neurology trainees learn these skills during residency while the depth of ultrasound education varies greatly worldwide. As a result, there is skepticism towards ultrasonography [25] that is largely based on the lack of knowledge of how to perform, interpret and use the results of ultrasound tests in clinical practice and research.

Indeed, ultrasound testing has shortcomings since it is very operator dependent. But so are most tests in medicine! The accuracy of ultrasound testing varies between practitioners of different skill, knowledge and experience. Even the most experienced of us are not invincible. Constant learning and improvement are keys to reaching the best possible outcomes of ultrasound testing.

Sonographers have to meet the requirements such set by the board examinations of the American Registry of
therapies. This approach is outlined in detail in a com-
localize the disease process and monitor the progress of
firm the vascular origin of patient symptoms, detect and
and often to go beyond "proven" (often meager) standards
use this information to select the best management strategy
should be tested in these trials. Ultrasound can be very help-
clinical trials." Not everything that we do as clinicians can or
skeptics would say, "it has not been tested in randomized
information finds no place in clinical decision-making as
continuing quality improvement are the keys to successful prac-
time assessment of patho-physiological changes and moni-
ting of patients with cerebrovascular diseases. Often, this
turns [26].
by ARDMS tests peripheral and carotid vascular testing
istered Physician Vascular Interpreter (RPVI) examination
specific to the neurovascular field including TCD. The Reg-
cludes [26].
In short, ultrasound remains an exciting field that offers
new possibilities and challenges. It requires investment of
time and effort to learn, yet it is rewarding in practice if you
master these skills. You will start to see the disease process
from new angles as real-time patho-physiological changes
unfold and hopefully become a better practitioner.

Practice of Ultrasound: an Introduction

Diagnostic Medical Sonographers (ARDMS, www.ardms.org) or other national and international boards and societies. Most vascular practitioners pass the Registered Vascular Technologist (RVT) examination that focuses mostly on vascular ultrasound “from jaw to toe” leaving transcranial Doppler (TCD) largely untested. International or regional requirements for technologists’ credentials also vary. The American Society of Neuroimaging and the Neurosonology Research Group of the World Federation of Neurology are making progress in providing certification examinations on all continents where there is an interest in verifying the knowledge and skills of physicians and sonographers. Interpreting physicians have to demonstrate competence through training such as Fellowship or by completing the required number of hours of continuing medical education in ultrasound methods and supervised interpretation of a set number of cases for each imaging modality. These require-
ments are outlined in the regulatory documents of the Inter-
societal Commission of Accreditation of Vascular Laborato-
ries (ICAVL, www.icavl.org) that recognizes two physician credentials outlined below as qualifications to serve as a
director of a vascular ultrasound laboratory.

The American Society of Neuroimaging (www.asnweb.org) also offers a peer-reviewed multiple-
choice proficiency examination in neurosonology that covers physics, clinical application and interpretation of the
carotid/vertebral and transcranial ultrasound methods. This
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ries (ICAVL, www.icavl.org) that recognizes two physician credentials outlined below as qualifications to serve as a
director of a vascular ultrasound laboratory.

In addition to credentialing, consistent application, local
validation of ultrasound testing and interpretation and con-
tinuing quality improvement are the keys to successful prac-
tices [26].
Ultrasonography offers a wealth of information, including real-
time assessment of patho-physiological changes and moni-
toring of patients with cerebrovascular diseases. Often, this
information might find no place in clinical decision-making as
skeptics would say, “it has not been tested in randomized
clinical trials.” Not everything that we do as clinicians can or
should be tested in these trials. Ultrasound can be very help-
ful in clinical decision-making if the results are produced in a
timely fashion and the practicing physicians are prepared to use
this information to select the best management strategy
and often to go beyond “proven” (often meager) standards
in the best interests of the patient.
I consider TCD and carotid duplex as an extension of the
neurological examination as these tests enable me to con-
firm the vascular origin of patient symptoms, detect and
localize the disease process and monitor the progress of
therapies. This approach is outlined in detail in a com-
panion book entitled Neurovascular Ultrasound Examination
and Waveform Interpretation. That book also contains basics
of ultrasound physics and fluid dynamics complementary
to this edition and provides more illustrative case exam-
pies of diagnostic findings and considerations in differential
diagnosis.
I am indebted to my peers, colleagues who challenged my
thinking, those who became my mentors through ongoing
debates and ultimately friends: Marsha Neumeyer, Joseph
Polak, John Pellerto and Charles Tegeler. The numerous
courses that we taught together made me in the first place
continuously learn ultrasound and re-think what I thought
I knew. Likewise on the clinical side, Andrew Demchuk,
James Grotta, Carlos Molina, Peter Schellinger and my team
at UAB contributed greatly to my continuing explorations of
stroke. I also gratefully acknowledge all contributors to this
book who donated their time and shared their expertise –
their chapters bring you on a continuing journey of learning
stroke and ultrasound. I would like to thank Rune Aaslid,
PhD, pioneer of TCD, for generously providing his original
drawing of the circle of Willis, as well as his input in advis-
ing me on cerebral hemodynamics.

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How to Perform Ultrasound Tests
Principles of Extracranial Ultrasound Examination

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Introduction

A simple observation gives origins to clinical examinations, analysis and scientific exploration. Being able to observe Nature at work or in distress often offers clues that clinicians and scientists need to get an idea as to what could be going on and come up with a hypothesis to explain it. Ultrasound, with its unprecedented temporal resolution, is an elegant tool to probe living tissues. This first chapter describes how we evaluate the extracranial vasculature, then subsequent chapters continue the journey into cerebral vessels, hemodynamics and specific disease states.

Anatomy of the cerebrovascular arterial system

The choice of transducer placement and subsequent repositioning determines the success of visualizing the target structures and staying with the spatial course of the pre-cerebral vessels. Therefore, sonographers performing vascular ultrasound examinations must think “in 3-D,” or three dimensions, about the vessel being investigated and put together transducer positioning with vessel intercept and further “go with the structure or flow” to complete scanning.

A sonographer should further imagine how this arterial segment would look on an angiogram. We strongly encourage those learning and interpreting ultrasound to be familiar with cerebral angiograms [1] since angiography is the gold standard for the assessment of the accuracy of ultrasound testing, and ultrasound performance is often judged by vessel appearance on invasive or non-invasive angiograms.

The following section deals with normal vascular anatomy and describes a standard protocol for carotid and vertebral duplex testing on the neck. More details of anatomy and angiographic images are provided in Chapter 3.

The common carotid artery

Scanning starts with a quick brightness-modulated (B-mode) surveillance in a transverse transducer position of the common carotid artery (CCA) up to its bifurcation. Color flow or power mode can be added to visualize flow in the vessel lumen (Figure 1.1).

On the right, the brachiocephalic trunk or innominate artery, arises from the aortic arch and then bifurcates into the subclavian artery and the CCA. On the left side, both the common carotid artery and the left subclavian artery usually originate directly from the aortic arch. The CCA is easily assessable on the neck where it runs in parallel with the jugular vein and the initial assessment starts right above the clavicle (Figure 1.2). It is further assessed in its mid-portion as the transducer slides cephalad over the sternocleido-mastoid muscle (Figure 1.3).

At approximately the level of the fourth vertebra, which is at the level of the upper border of the thyroid cartilage, the CCA bifurcates into the internal and external carotid arteries (Figure 1.4). The carotid bulb represents dilatation at the distal CCA extending into the proximal internal carotid artery. The carotid bulb bears unique flow patterns yielding a boundary separation zone and its wall has numerous baro- and chemo-receptors. The size and location of the carotid bulb are variable.

Most atherosclerotic disease occurs at the level of the bifurcation due to marked changes in vessel geometry resulting in increased shear stress, fluid stagnation and increased particle residence time on the posterolateral wall of the bulb [2].

The internal carotid artery

Beyond the carotid bulb, the internal carotid artery (ICA) returns to a normal caliber (Figure 1.5) and courses in a relatively straight line up the neck into the skull to supply blood...
PART I How to Perform Ultrasound Tests

Figure 1.1 Transverse positioning of the duplex transducer depicts carotid bifurcation on the neck. Arrows indicate a proximal initial placement of the probe and its ascent to the bifurcation as the initial step to extracranial vascular examination. The left side of the ultrasound B-mode and color flow image is oriented towards the midline. Red color shows arterial flows, blue indicates the jugular vein.

Figure 1.2 After transverse sweeps, a longitudinal position of the probe yields depiction of the proximal common carotid artery close to its origin from the brachio-cephalic trunk on the right side of the neck. Note that ultrasound image is aligned with the middle of the vessel by keeping “the ends of pipe open.” The left side of the ultrasound image is oriented cephalad. Doppler sampling shows the velocity spectra at a 60° angle of insonation.

Figure 1.3 A longitudinal view of the mid-cervical portion of the right carotid artery shows B-mode, color flow and Doppler spectra of the artery and flow through it.
CHAPTER 1 Principles of Extracranial Ultrasound Examination

flow to the eye and brain. As a rule, the ICA has no branches within the neck. After entering the skull, the ICA makes an S-shaped curve in the region of the carotid siphon. The ICA entrance to the skull marks a vulnerable area where arterial wall dissections may occur due to fixed ICA position. The first major branch of the ICA is the ophthalmic artery that supplies the eye. After giving off the ophthalmic artery, the ICA divides into the middle cerebral artery (MCA) and the anterior cerebral artery (ACA), a part of the circle of Willis. This is covered in Chapters 2 and 3.

The external carotid artery

The extracranial carotid artery (ECA) supplies the muscles of the face, forehead and scalp (Figure 1.6). To switch between the ICA and ECA, a sonographer often must reposition the transducer from lateral to more medial angulation since both vessels are seldom visualized together in one plane for sufficient interrogation. The ECA has branches that could be visible while scanning its proximal segment. The ICA divides into eight branches on the neck. Several of these branches, i.e. ascending pharyngeal, facial, internal maxillary and superficial temporal arteries, communicate via anastomoses with the ICA. The occipital artery is the only ECA branch that communicates with the vertebral artery circulation. It is important to recognize these branches because the ECA fairly often becomes a collateral source for blood flow to the brain when the ICA is critically stenosed or occluded.

The vertebral artery

The vertebral arteries (VA) arise from the subclavian arteries and its origin can be found with transducer sliding towards the clavicle and aiming deep and lateral to the CCA (Figure 1.7). The VA passes medially in the neck to enter the bony canal at the C6 vertebrae and it further courses cephalad through the transverse processes of the vertebrae (Figure 1.8). It enters the base of the skull by looping around the atlas and ascending through the foramen magnum. At this point, the right and left vertebral arteries join together to form the basilar artery. The basilar artery terminates in the posterior cerebral arteries, which make up the posterior portion of the circle of Willis.

Components of ultrasound examination

Continuous wave (CW) Doppler

Although this technology is now regarded more of historic interest due to technological advances in imaging, knowledge of CW Doppler is required for board examinations and occasionally the skill of using the so-called “pencil probe” may be useful.

Dr Eugene Strandness and co-workers first reported the use of a transcutaneous flowmeter to evaluate occlusive arterial disease in 1966 [3]. Extracranial carotid and vertebral examinations with CW Doppler were reported by Drs Merrill Spencer and Michael von Reutern and colleagues in the 1970s [4,5].
PART I How to Perform Ultrasound Tests

Figure 1.6 Insonation of the ECA: color flow image shows a branch while Doppler spectra display a characteristic high resistance waveform.

Scanning direction

Figure 1.7 Insonation of the origin of the vertebral artery. Arrows show the further extent of the vertebral artery examination on the neck.

Figure 1.8 Doppler spectra in a proximal cervical segment of the vertebral artery visualized with B-mode and color flow.
Insonation with CW probe

With this technology, one crystal continuously emits the signal and another crystal continuously receives returned echoes, and this “non-imaging” transducer looks like a pencil (Figure 1.9). CW Doppler displays Doppler frequency shifts including maximum frequency trace without an artifact due there being no limitations related to pulse repetition frequency. Current CW systems can differentiate between positive and negative Doppler shifts and create a bi-directional spectral signal that shows flow direction as towards or away from the transducer. However, CW Doppler shows no information regarding the structure, i.e. image, or the depth from which the signals originated.

The advantage of this ultrasound test is its ability to display Doppler frequency shifts from moving objects without an artifact called aliasing. With the recent development of direct imaging and pulsed wave Doppler methods, CW Doppler is rarely performed and is not reimbursed in the United States as a sole test used for evaluation of the carotid vessels. Perhaps the only remaining indications for CW Doppler for carotid arteries are extensive (>2 cm) shadowing of the bifurcation, arterial lesions extending above the level of lower jaw or a quick bifurcation screening before or with the bifurcation, arterial lesions extending above the level of lower jaw or a quick bifurcation screening before or with the bifurcation, arterial lesions extending above the level of lower jaw or a quick bifurcation screening before or with the bifurcation, arterial lesions extending above the level of lower jaw or a quick bifurcation screening before or with the bifurcation.

1. Shadowing (no image can be generated along ultrasound beam axis behind a bright reflector). Changing the transducer position and planes of insonation may minimize shadow appearance. Shadows can originate from perpendicular insonation of vessel walls, plaque calcification (Figure 1.7) and transverse vertebral processes (Figure 1.3).
2. Reverberation (multiple bright echoes that often have a regular shape and layered position are displayed along the axis of ultrasound beam when echoes bounce many times between two strong reflectors).
3. Mirror image [a false image (also known as phantom image or reflection artifact) is created when obliquely scanning a strongly reflecting boundary]. Vessel visualization in transverse and longitudinal planes often resolves confusion associated with this artifact.
4. Plane-of-section (three-dimensional structure is inadequately displayed on a two-dimensional monitor). Using imagination for three-dimensional spatial relationships, the transducer position should be changed to generate adequate sectional planes.

B-mode imaging is used to identify the carotid and vertebral arteries, carotid intima-media complex, atherosclerotic plaques and anatomic anomalies. B-mode imaging can also be used to perform intracranial studies where it shows contralateral skull line, midline structures including the third ventricle and brain parenchymal structures.
PART I How to Perform Ultrasound Tests

The color-flow Doppler image
Color-coded Doppler flow image (CDFI) displays the average (or mean) shifts in the frequency of returned echoes backscattered from moving objects, usually red blood cells. The color scale can be selected manually, ranging from two colors (red and blue) to a rainbow palette. At least two distinctly different colors are used to display clearly the direction of flow relative to transducer midline (Figure 1.10). According to the Doppler effect, objects moving towards the transducer will increase the frequency of backscattered echoes relative to emitted frequency and vice versa. However, color assignments are operator-dependent. Therefore, CDFI is used to identify moving blood and display the direction of flow. No Doppler frequency shift occurs at a 90° angle between ultrasound beam and moving blood stream (Figure 1.8). CDFI often contains artifacts:
1. Aliasing (abrupt change from the maximum velocity in one flow direction to the maximum velocity in the opposite direction without crossing the zero line). It can be present in a normal vessel if the scale settings are inadequately low to display flow velocity, i.e. a sonographer uses a low pulse-repetition frequency (Figure 1.9). It can also be present with maximum scale settings in stenosed vessels due to elevated flow velocities. Scale setting control and comparison of vessel course and B-mode findings help to differentiate imaging artifact from pathological finding.
2. “Bleeding” (the presence of moving blood outside the vessel). This artifact can be produced by an oblique strong reflector (mirror image) or by tissue motion adjacent to the vessel. In both circumstances, changing the transducer position and color gain setting helps to optimize the image (Figure 1.10).

Occasionally, CDFI may be unable to depict blood flow since its spatial resolution is lower than the B-mode image. Also, there is a trade-off between B-mode and superimposed CDFI images: larger CDFI boxes require slower frame rates that decrease B-mode resolution and vice versa. CDFI may not be able to display blood flow adequately in tortuous and deep-located vessels and also vessels affected by the low flow states, i.e. near-occlusion. Other forms of flow imaging may be used in these circumstances.

The power Doppler image
Power Doppler imaging displays color-coded intensities of the returned echoes that contain Doppler frequency shifts. Unlike CDFI, power mode Doppler shows direction-independent changes in the energy of signals backscattered by moving objects. Therefore, power mode images are usually created with brightness-adjusted uni-color scales (Figure 1.11). Power mode images show the course of the vessel without color change due to flow direction. Power mode can be used to visualize tortuous and deep-located vessels, branches and slow-moving blood. “Flashing” is the most common artifact that is created by tissue motion and, similarly to “bleeding,” displays artifactual flow signals outside the vessel lumen. This can be corrected by changing the gain settings and color box size.

The color velocity image
The color velocity imaging (CVI) display is similar to CDFI; however, the color-encoded velocities are derived from time-domain processing of returned echo signals. For example, the CVI image represents the movement of red blood cell clusters in time along the vessel course. It allows a better trade-off between B-mode and color flow information in terms of image resolution due to better utilization of scan lines. CVI can also display functional flow lumen better. It is also used in some laboratories to calculate flow volume estimates in the carotid arteries.
CHAPTER 1 Principles of Extracranial Ultrasound Examination

ICA stenosis

Figure 1.12 B-flow imaging of the carotid stenosis.

B-Flow and compound imaging
Brightness-mode display can also be used to generate flow images since moving blood changes the strength of reflected signals relative to surrounding structures. Combined with electronic focusing and multiple focal zones, such images can provide high-resolution structural scans (Figure 1.2) and superimpose flow signals in gray scale over a B-mode image (Figure 1.12). The B-flow scans avoid aliasing and offer potentially better trade-off between tissue motion and moving blood signals.

Harmonic imaging
An emitted frequency of a diagnostic ultrasound pulse wave passing through tissue can change due to reflection off a moving object (Doppler shift) or during faster sound transmission through fluid compressed at the peak intensity of the ultrasound wave (harmonics). This frequency change occurs mostly during wave propagation (less during reflection). The result is the appearance of the second harmonic frequency that is twice the emitted frequency. This mechanism of non-linear interaction of ultrasound with body tissues allows the use of harmonic frequencies to image tissues with and without contrast substances, and new-generation duplex scanners provide this option. Potential clinical utility of harmonic imaging in cerebrovascular ultrasound includes application of contrast agents for tissue perfusion studies, including brain parenchyma, differentiation of a complete occlusion from subtot al stenosis and better delineation of plaque and vessel wall morphology.

Doppler velocity spectral display
A pulse-wave ultrasound beam can also be used to detect Doppler shift in the returned echoes since moving blood or tissues will change the emitted frequency. This phenomenon is used to measure flow velocity simultaneously with structural and color flow imaging. To obtain velocity values close to real speed of blood, angle correction is applied, which is discussed in the scanning protocol in the next sub-section.

Extracranial duplex ultrasound examination technique and scanning protocol
The extracranial duplex examination should include transverse and longitudinal B-mode scans of the vessels. Examination can start with transverse scanning since it allows fast identification of CCA, jugular vein, the level of bifurcation and the presence of atherosclerotic disease. The transverse examination begins with the most proximal segment of the common carotid artery following its course towards the distal portion, passing through bifurcation and ending at the level of the mandible with visualization of the distal cervical segment of the internal carotid artery (Figure 1.13). The transverse plane permits appreciation of vessel diameter, presence of pathology and anatomic anomalies. The examination is repeated in the longitudinal plane (Figures 1.1 and 1.2), beginning again with the most proximal segment of the CCA and extending the scan throughout the bifurcation, internal and external carotid arteries. The vertebral artery is examined at its origin and also in the mid-cervical segment of the neck (Figure 1.3).

To optimize the gray-scale image, set the dynamic range to 40–50 dB and the time-gain compensation (TGC) as appropriate to the depth of the common carotid and vertebral arteries.

Imaging in the transverse plane
1 With the patient’s head turned slightly away from the side being examined, place the ultrasound probe low on the neck, anterior to the sterno-cleido-mastoid muscle, just above the clavicle. The left side of the image should be oriented towards midline structures, i.e. trachea.
2 Locate the proximal segment of the CCA in the transverse plane. Slowly move the probe along the length of the CCA.
3 At the distal end of the CCA, locate the dilatation that identifies the carotid bulb.
4 Slowly move the probe through the region of carotid bulb and note the bifurcation into the internal (ICA) and external (ECA) carotid arteries.
5 Follow the course of the ICA and ECA to the level of mandible. Document any evidence of pathology, vessel tortuosity and abnormal anatomy.

Imaging in the longitudinal plane
1 Return to the proximal segment of the CCA with the ultrasound probe rotated to image in the longitudinal axis. The left side of the image should be oriented cephalad.
2 Begin with the probe placed anterior to the sterno-cleido-mastoid muscle.
PART I How to Perform Ultrasound Tests

Figure 1.13 Transverse scanning of the proximal CCA, bifurcation, ECA and ICA (from left to right).

3 Image the widest longitudinal axis of the CCA by directing the sound beam perpendicular to the anterior wall of the vessel.
4 Optimize the image so that the normal linear reflectivity of the arterial wall is apparent.
5 Slowly move the probe along the course of the vessel and into the carotid bulb.
6 With the distal CCA and bulb in view, slowly rock the transducer side-to-side to reveal the origins of the internal and external carotid arteries. Care must be taken to angle the probe along the origins to avoid transecting the views of each artery.
7 In turn, follow the courses of the ICA and ECA, optimizing the image for accurate evaluation of anatomy and pathology. Document any evidence of pathology, vessel tortuosity or abnormal anatomy.

Color flow ultrasound evaluation of flow dynamics

1 Return to the longitudinal image of the proximal CCA.
2 Choose the appropriate color pulse repetition frequency (PRF) by setting the color velocity scale for the expected velocities in the vessel. For normal adult arteries, the velocity range is usually around or under 100 cm s⁻¹ (or 2.5 kHz Doppler frequency shift). Note that most criteria will use a 125 cm s⁻¹ cut-off for velocities elevated due to carotid stenosis. Adjust the scale further to avoid systolic aliasing (low PRF) or diastolic flow gaps (high PRF or filtering) in normal vessels.
3 Optimize the color power and gain so that flow signals are recorded throughout the lumen of the vessel with no “bleeding” of color into the surrounding tissues.
4 Avoid using large or wide color boxes since this will slow frame rates and resolution of the imaging system. Use color boxes that cover entire vessel diameter and 1-2 cm of its length. Align the box, i.e. select appropriate color flow angle correction, according to the vessel geometry and course.

Doppler spectral evaluation of flow dynamics

1 Return to the longitudinal image of the CCA.
2 Use the color flow image as a guide for Doppler examination (Figure 1.14).
3 Begin the examination using a Doppler sample volume size of 1.5 mm positioned in the middle of a normal vessel (Figure 1.14).
4 Consistently follow one of the choices for angle correction: parallel to the vessel walls or to the color flow jet.
5 Adjust the Doppler spectral power and gain to optimize the quality of the signal return.
6 Slowly sweep the sample volume throughout the length of the CCA, bulb, ICA and ECA.
7 Perform temporal artery tapping when insonating ECA to differentiate between the ECA and ICA flows. Also note the presence of arterial branches that may be present at the proximal ECA stem.
8 Identify regions of flow disturbance or where flow is absent.
9 Record flow patterns in the proximal and distal CCA, the proximal, mid and distal ICA and the proximal ECA.
CHAPTER 1 Principles of Extracranial Ultrasound Examination

Figure 1.14 Placement of sample volume in the CCA using color flow image as a guide. A small (1.5 mm) gate is used for Doppler spectral measurement and a large (10 mm) gate is used for the flow volume measurements.

at appropriate angles of insonation. Additionally, include Doppler spectral waveforms proximal, within and distal to all areas where flow abnormalities were observed.

10 Locate the origin or proximal segment of the vertebral artery (Figure 1.7). Record flow patterns paying careful attention to flow direction. Follow accessible cervical segments of the vertebral artery (Figure 1.8). Change the angulation of the color box and Doppler sample along with the course of the artery.

Extracranial duplex examination should provide the following data

1 Peak systolic velocity in all vessel segments.
2 End-diastolic velocity in all vessel segments.
3 Ratios of the ICA to CCA peak systolic velocities.
4 Documentation of the Doppler spectral waveform morphology from the CCA, ICA and ECA.
5 Flow direction and peak systolic velocity of the vertebral arteries.
6 Views demonstrating the presence and location of pathology.
7 Images of plaque morphology and surface features.

Tips to improve accuracy

1 Consistently follow a standardized scanning protocol.
2 Perform a complete examination of the carotid and vertebral arteries.
3 Sample velocity signals throughout all arterial segments accessible.
4 Use multiple scan planes.

5 Take time to optimize the B-mode, color and spectral Doppler information.
6 Videotape or create a digital file of the entire study including sound recordings.
7 Always use the highest imaging frequencies to achieve higher resolution.
8 Account for any clinical conditions or medications that might affect velocity.
9 Integrate data from the right and left carotid and vertebral arteries.
10 Do not hesitate to admit uncertainty and list all causes for limited examinations.
11 Expand Doppler examination to intracranial vessels when indicated.

Tips for optimizing color flow set-up

1 According to standardized protocols, the carotid bifurcation should be to the left of the image. This orientation should then clearly indicate the appropriate direction of flow in the common carotid artery and jugular vein. The arterial and venous flow directions are then given color assignments with respect to flow towards or away from the transducer. Traditionally, flow towards the transducer is assigned red (common carotid) and flow away from the probe is assigned blue (jugular vein). The direction of flow relative to the probe will change if the probe is rotated 180° or if the color box is steered in the opposite direction, i.e. the vein will appear red whereas the artery will appear blue. When this occurs, the color should be changed back to the original assignment to avoid confusion. It must also be noted that the color will change along the course of an artery if the flow direction varies throughout the cardiac cycle (triphasic, to-and-fro) or if the vessel changes direction relative to the orientation of the sound beam.

2 The zero baseline of the color bar (PRF) is set at approximately two-thirds of the range with the majority of frequencies allowed in the red direction (for flow towards the brain). This setting allows you to display higher arterial mean frequency shifts (velocities) without aliasing artifacts. You should make allowance for some flow in the reverse (blue) direction to allow for changes in flow direction (i.e. ICA bulb, post-stenotic dilatation). When the transducer is rotated 180°, the color will change (note point 1 above) and the zero baseline will shift with the color changes to accommodate flow in the forward direction. You will need to adjust both the color assignment and the zero baseline to the initial set-up for consistency.

3 The color PRF and zero baseline may need to be readjusted throughout the examination to allow for the changes in velocity that occur with tortuosity and stenosis. It is important to adjust the PRF in the following situations:
PART 1 How to Perform Ultrasound Tests

Examination of the carotid bulb –

The color differentiation scale should be set to detect and clearly visualize the slower flow in the boundary separation zone. The range (PRF), however, may need to be set higher to detect increased velocities in the region adjacent to the flow divider.

In the presence of stenosis –

The color PRF should be increased to display the high velocities and to avoid aliasing.

In the post-stenotic zone –

The color PRF should be decreased to observe the lower velocities and flow direction changes, if any, found in the region of turbulent flow just distal to the stenosis.

When bruits are encountered –

The color PRF should be decreased to detect the lower frequencies associated with a bruit. Usually, the frequency of these bruits is less than 1 kHz.

When occlusion is suspected –

The color PRF should be decreased to detect the pre-occlusive, low velocity, high resistance signal associated with critical stenosis or occlusion and to confirm absence of flow at the site of occlusion.

1 The color wall filter should be set as low as possible. You should note that the color wall filter may automatically increase as you increase the PRF. You may need to decrease the wall filter manually when you decrease the color PRF.

2 The ensemble length (color sensitivity) should be around 12 in systems where this is an adjustable control. You can increase the ensemble length in regions where you want more sensitive color representation. It is important to remember that the frame rate will decrease when the ensemble length is increased (see also point 8 below). There are no circumstances when the ensemble length would be decreased during an extracranial carotid duplex examination.

3 The angle of the color box should be changed to obtain the most acute Doppler angles between the scan lines and the direction of blood flow. This will result in better color display because of more suitable Doppler angles. The angle should always be equal to or less than 60°. Because linear array transducers are steered at angles of 90 and 70° from the center of the array, this may require a “heel–toe” maneuver with the transducer on the surface of the skin to adjust the position of the vessel within the color box. An alternative would be to change physically the orientation of the transducer 180°.

4 The color bar indicates increasing Doppler frequency shifts, i.e. increasing velocities. Note that close to the zero baseline, the colors are the darkest. As the velocity increases, the color becomes lighter. You should select colors so that the highest frequency shifts in each direction are of high contrast to each other so that you can readily detect aliasing. For example, you could set the color selections so that low to high velocities are seen as dark blue to light green to aqua in one direction and red to orange to yellow in the opposite flow direction. Aliasing would then appear as aqua adjacent to yellow.

5 The frame rate should be kept as high as possible to capture the very rapid change in flow dynamics that occur with stenosis, especially in the region of the carotid bulb. Remember that frame rate is affected by:

   - PRF – Frame rate decreases with decreasing PRF.
   - Ensemble length – Increasing the color ensemble length will decrease the frame rate.
   - Width of the color box – Increased width will decrease the frame rate.
   - Depth – Deep insonation decreases frame rate.

6 The color box should be kept to a size that is adequate for visualizing the area of interest and yet small enough to keep the frame rate at a reasonable number, approximately 15 or more, to ensure adequate filling of the vessel. The frame rate is usually displayed in hertz on the monitor.

7 The color gain should be adjusted throughout the examination to detect the changing signal strength. If the color gain is not properly adjusted, some color information may be lost or too much color may be displayed. In this case, you will see color in areas where there should be no flow. The gain should initially be adjusted to an “over-gained” level, with color displayed in the tissue and then turned down until the tissue noise just disappears or is minimally present.

8 This is the level at which all color images should be assessed. In situations where there is very low flow or questionable occlusion, an “over-gained” level may be advantageous to show any flow that might be present, e.g. total occlusion versus a near-occlusion or critical stenosis.

References


