Procedural Manual of Neurosonology

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Edited by

Jose C. Navarro and Vijay K. Sharma

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FOREWORD

Stroke systems of care undergo rapid changes and the field of Vascular Neurology faces new challenges. Emphasis on imaging in patient selection for reperfusion therapies placed snapshot assessment of occlusion location and estimates of core and penumbra as key elements in education of next generation of clinicians caring for stroke patients. The use and knowledge of cerebrovascular ultrasound testing decrease leaving these skills a privilege of few.

A stroke clinician should be able not only to determine if a patient is eligible for systemic thrombolysis or endovascular treatment but also to ascertain stroke pathogenic mechanisms across all patients. The key question in Vascular Neurology is not just What? and Where? but **Why?** A normal CT angiogram in a patient with severe or fluctuating symptoms poses more questions. Ultrasound brings a unique option of evaluating cerebral hemodynamics in real time with assessments being repeatable as often as necessary. The ability to perform various cerebrovascular ultrasound tests as an extension of the neurological examination and knowledge how to interpret cerebral and systemic hemodynamic findings distinguishes a stroke clinician capable to attend to needs of the most complex patients and tailor make treatment or secondary prevention solutions based on these individual pathogenic mechanisms. Ultrasound is entirely complementary to CTs, MRIs and catheter angiography, and these vascular tests should be taught in all stroke fellowships worldwide, ideally starting during residency.

My dear friends and colleagues Jose Navarro and Vijay Sharma have put together a practical manual of most commonly used cerebrovascular ultrasound tests and assembled the group of contributing experts that represent leading stroke specialists from Asia. This is a welcome contribution that complements existing literature mostly from European and US experts. A perspective for countries where advanced multi-modal imaging for stroke is not universally available makes this book a valuable resource particularly for clinicians facing challenges in caring for stroke patients with limited resources. In addition, residents and fellows should find this informative to learn tests and key applications. Existing

ultrasound laboratories and technologists should also have updated scanning protocols and operation manuals, all good reasons to have this book.

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PREFACE

In spite of the tremendous advances in the field of vascular neuroimaging, the role of ultrasound (Transcranial Doppler, Transcranial Color-Coded Duplex, and Carotid ultrasonography) in the diagnosis and management of cerebrovascular disorders can still be relied upon. The accuracy of neurovascular ultrasound against vascular imaging is quite acceptable. Certain ultrasound tests can even be considered superior to other modalities. The detection and monitoring of microembolic signals in real-time can be achieved only with ultrasound. Vasomotor reactivity of brain vasculature demonstrates the downstream effects of a significant arterial stenosis and can be performed at the bedside by TCD. This can aid the clinicians in a confident risk stratification, especially for patients undergoing major surgical procedures. TCD monitoring during intravenous thrombolysis may identify the site of arterial occlusion, recanalization and re-occlusion in real-time. Furthermore, its portability and being a non-invasive test make it advantageous as compared to other vascular imaging techniques. TCD has acceptable accuracy parameters for test performance and reproducibility.

A group of neurosonologists, mostly from Asia pooled together their talent, time and effort to create this manual. It is not intended to be a textbook or a reference book of neurosonology. The main purpose of this manual is to have an immediate access for clinicians and sonographers, trainees and students performing neurosonological evaluations. Chapters are written by several authors to reflect diverse expertise, experience and techniques put together in a concise manner.

We wish to express our deepest gratitude to our families for support given to us while working on this project. It also goes to our patients, trainees and colleagues in our respective departments. Lastly, we thank Cambridge publishing for believing in us and providing the opportunity to have this manual published.

Jose C. Navarro, MD, MSc
Vijay K. Sharma, MD

APPLIED ULTRASOUND PHYSICS AND INSTRUMENTATION

AMIT BATRA, JOSE C. NAVARRO, KOMAL KUMAR, AND VIJAY K SHARMA

For a better understanding of a technology, users should know the basic principles, components, simple operations and interpretations of various research findings. Cervical duplex (CDU) and transcranial Doppler (TCD) ultrasonography are routinely performed for hemodynamic evaluations in patients with cerebrovascular ischemia. Both CDU and TCD are essential components of comprehensive stroke centers.

Ultrasound physics is considered quite difficult. Often, it is said that "if you do not want someone to learn clinical ultrasonography, teach him physics in detail. He will certainly run away! In this chapter, we describe some of the basic principles and the relevance of ultrasound physics. Although, this is not comprehensive, this chapter contains all the essentials needed by a beginner. Readers interested in becoming experts or planning to take the credentialing examinations are advised to understand ultrasound physics in greater detail.

1. **What is ultrasound?**
   A normal human ear can hear sound frequencies from 20-Hz to 20,000- Hz. Sounds with frequencies of more than 20,000 Hz are inaudible to the human ear and called ultrasound waves.

2. **What are the basic characteristics of sound?**
   Sound is a longitudinal, mechanical, and pressure wave that travels in a straight line. It requires a medium for its travel. The speed of sound is determined by the medium through which it propagates (and has no relationship with the frequency, amplitude, power, or any other variable). The speed of the propagation of sound in air is 330 meters per second, while it becomes 1,540 meters per second (1 mile per second) in soft tissues.

Ultrasound frequencies emitted by the transducers used in the commercial ultrasound machines used for medical purposes are between 2- and 22-MHz. While a lower frequency ultrasound travels for longer distances (2-MHz ultrasound travels up to 150 mm), the imaging resolution is poor. On the other hand, higher frequency ultrasound transducers can image only superficial tissues but with a high resolution. For example, excellent tissue resolution needed for carpal-tunnel imaging uses 22-MHz ultrasound. The commonly performed cervical duplex ultrasonography uses transducers with frequencies ranging from 5- to 12-MHz.

3. What is the Doppler effect?

Whenever a relative motion occurs between the sound source and the observer, the frequency heard by the observer is different from the originally produced sound frequency. Accordingly, when the distance between the source and the observer increases, the latter hears a lower frequency (negative Doppler shift). On the other hand, the observer hears a frequency higher than the original if the distance between him and the source is reduced (positive Doppler shift). This phenomenon was described by Christian Doppler in 1842. In general, the Doppler shift is calculated with the following formula:

$$f_D = \frac{2f_o \, v \cos \theta}{c}$$

Where f_D is frequency shift, f_o is original frequency, v stands for velocity of sound, $\cos\theta$ is the angle of insonation, and c is a constant.

The constant (c) changes with the ultrasound frequency. Therefore, the Doppler frequency shift is independent of the originally produced frequency. This explains why the flow velocities (derived from the frequency shift) are the same whether one uses a transducer with a frequency of 4-MHz or 8-MHz.

According to this formula, the angle of insonation is an important determinant of the Doppler shift. Sonographers should remember at least the following:

a. Cosine of 0 degree = 1
b. Cosine of 180 degree = -1
c. Cosine of 60 degrees = 0.5

These numbers mean that if an arterial segment is insonated parallel to the blood flow (the angle of insonation is 0 or 180 degrees), the Doppler shift represents the real flow velocity. On the other hand, if an artery is insonated at 60 degrees to the blood flow, the Doppler shift (hence, the flow velocity) measured by the machine would be about 50 percent lower than the real. This is important since most of the flow velocities obtained during cervical duplex sonography are obtained at 60 degrees of insonation.

4. How is ultrasound produced?

Ultrasound is produced when a small amount of current is passed through a piezoelectric crystal (lead zirconate titanate). Note that '*piezo'* means pressure. The crystals are very stable and have a very long life. Their piezoelectric nature gets destroyed only with hard physical impact. Therefore, sonographers should always avoid dropping the transducer (see figure 1) on the floor.

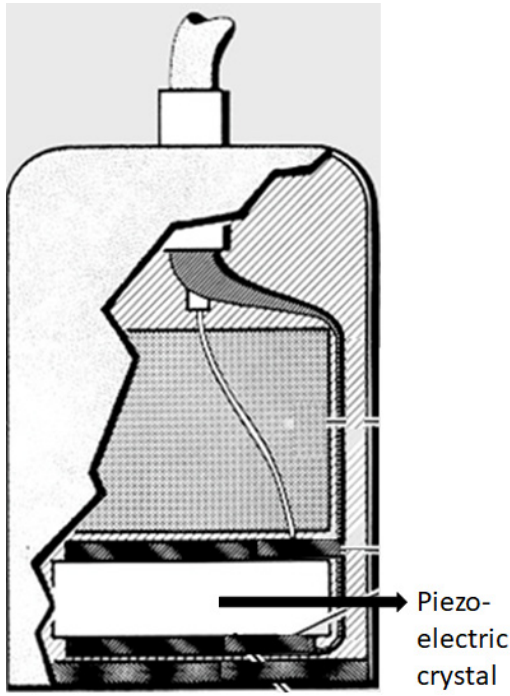

Figure 1.

5. What is the difference between 'continuous wave' and 'pulsed wave' ultrasound?

Initial ultrasound machines used the continuous wave (CW) ultrasound, in which one transducer continuously emitted ultrasound waves, while the other transducer received the waves reflected back from various tissue interfaces. Therefore, the instruments were bulky. Although, these machines could detect the flow and its direction, they were unable to tell the distance (or depth) between the source and the reflector. Therefore, CW ultrasound are "range ambiguous."

In pulsed wave (PW) ultrasound systems, instead of emitting continuously, the transducer emits ultrasound waves in a burst or bundle only for a fraction, and then starts working as a receiver for the reflected waves. Most of the diagnostic transducers emit ultrasound for 1% of the time (also called duty factor) and listens for 99% of the time. Since the time of emission of ultrasound and the time of receiving are known, the distance from where the waves are reflected can be assessed. Therefore, the PW ultrasound systems are "depth discriminant."

The operators should understand the important concept of "aliasing". When the Doppler shift is more than half of the pulse repetition frequency (PRF, i.e., the number of ultrasound bundles emitted per second), PW ultrasound systems are unable to detect the flow correctly (remember that the blades of a fan appear as moving counterclockwise slowly when the fan attains fast speed). This is called aliasing, and it is defined by the Nyquist limit. This is one of the major limitations of PW ultrasound systems. On the other hand, the CW systems are not limited by aliasing (the Nyquist limit is maximum). Aliasing may be observed on color flow imaging (figure 2) as well as on Doppler spectra (figure 3).

Current, commercially available equipment use PW ultrasound.

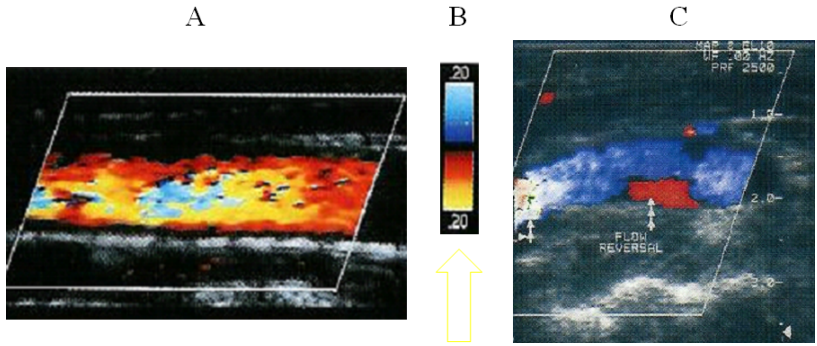

Figure 2. Panel A shows aliasing in color mode. Panel B shows the color scale. Shades of red are in one direction, while the shades of blue lie in the opposite direction. Importantly, the center of this color scale is black. It means that if there is a change (reversal) in the direction of blood flow, it has to go from red to black to blue or the other way around (panel C). If there is no black color in between the colors on the two sides of the color scale, this becomes aliasing (A).

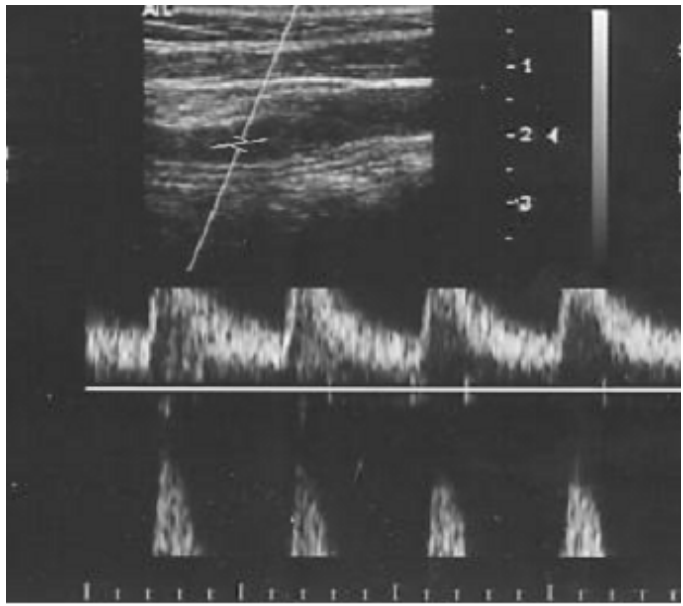

Figure 3. Aliasing on Doppler spectra. Due to the lower pulse repetition frequency (or low scale), the machine cannot measure the peak velocities. The top of the spectra appear as cut from the top and pasted below.

Some methods of correcting Aliasing (figure 4):

a. Increase PRF (scale)
b. Move baseline up or down
c. Use the CW ultrasound

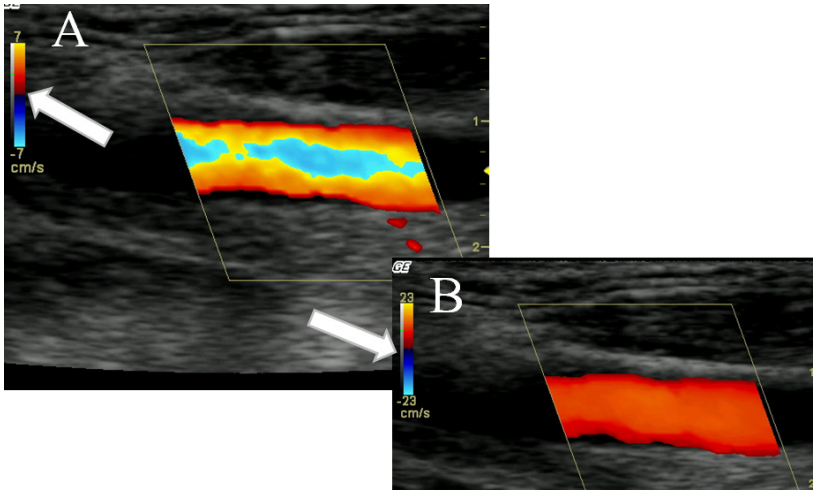

Figure 4. Methods of correcting. Panel A shows aliasing on color-flow (due to low scale setting). Aliasing gets corrected (un-aliasing) on Panel B as the scale is increased.

6. What are the basic principles of fluid dynamics?

All principles of fluid dynamics presume that a flow moves in a straight tube and the stenosis (when it occurs) is concentric (or axis symmetric). Some important concepts are:

a. Blood flows in layers (laminar) and the central layer is fastest. On the other hand, the flow is minimal along the arterial wall (parabolic). Figure 5 shows this phenomenon.

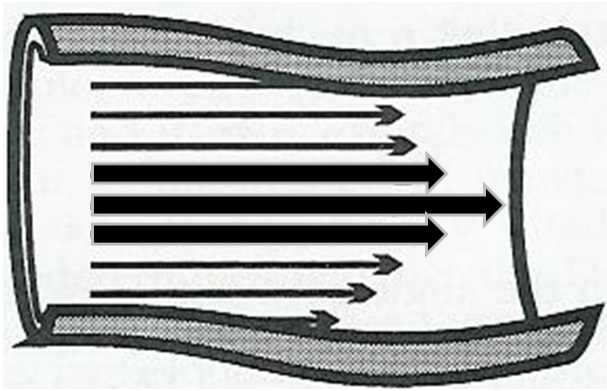

Figure 5. Laminar and parabolic flow. The slow flow along the arterial wall serves as a protection from shearing stress and reduces wear and tear.

b. Poiseuille's law

$$Q = \frac{\Pi(P1 - P2)r^4}{8L\eta}$$

Where Q = Blood flow

P1-P2 = pressure difference

r = radius

L = length

η = viscosity

The most important clinical applications of this formula are:

1. The blood-flow volume is directly proportional to the fourth power of radius. Therefore, reduction of the radius to half will decrease the flow volume by sixteen times (½ X ½ X ½ X ½).
2. The flow volume reduces with increasing length of the stenosis.

7. What are the basic components of an ultrasound machine?
The components of the current commercial diagnostic ultrasound systems are:

A. Transducer probe
B. Transducer pulse controls
C. Central processing unit
D. Display
E. Keyboard/cursor
F. Disk storage device
G. Printer

Therefore, an ultrasound equipment is just a specialized computer.

8. What is the resolution of an ultrasound machine?
Resolution is the ability of the machine to differentiate between two adjacent structures. It is of two types: axial and lateral (figure 6).

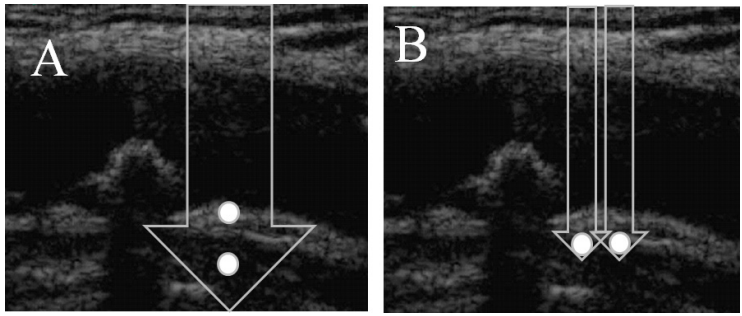

Figure 6. Axial resolution (A) differentiates between superficial and the deeper structures. It is directly dependent on the frequency of the ultrasound transducer (higher frequency = higher axial resolution). Lateral resolution (B) is the ability of the equipment to differentiate two adjacent structures. It depends on the beam width.

9. Which transducer frequency is good for me?
A higher frequency ultrasound has higher axial resolution. However, it does not penetrate deeply. On the other hand, a lower frequency ultrasound can penetrate deeply but has low resolution.

Thus, a sonographer compromises the resolution of the ultrasound by its ability to scan deeper structures. This compromise is called “trade-off.”

10. What is ALARA?

ALARA stands for “as low as reasonably achievable.” Ultrasound is a form of energy. It undergoes reflection, refraction, and absorption at various tissue interfaces during its propagation among various tissue interfaces. The absorbed ultrasound may get converted into heat energy (thermal side effect) and cause tissue damage. The other biological effect is cavitation. It occurs owing to the fast speed of transmission, which leaves a vacuum behind. This may lead to a collapse of the tissues with resultant damage.

Although the commercially available ultrasound systems are quite safe for human use, sonographers should still follow the ALARA principle.

Basic Operations of the Cervical Duplex Machine

Many companies manufacture cervical duplex machines. An example with various parts of the system is shown in figure 7.

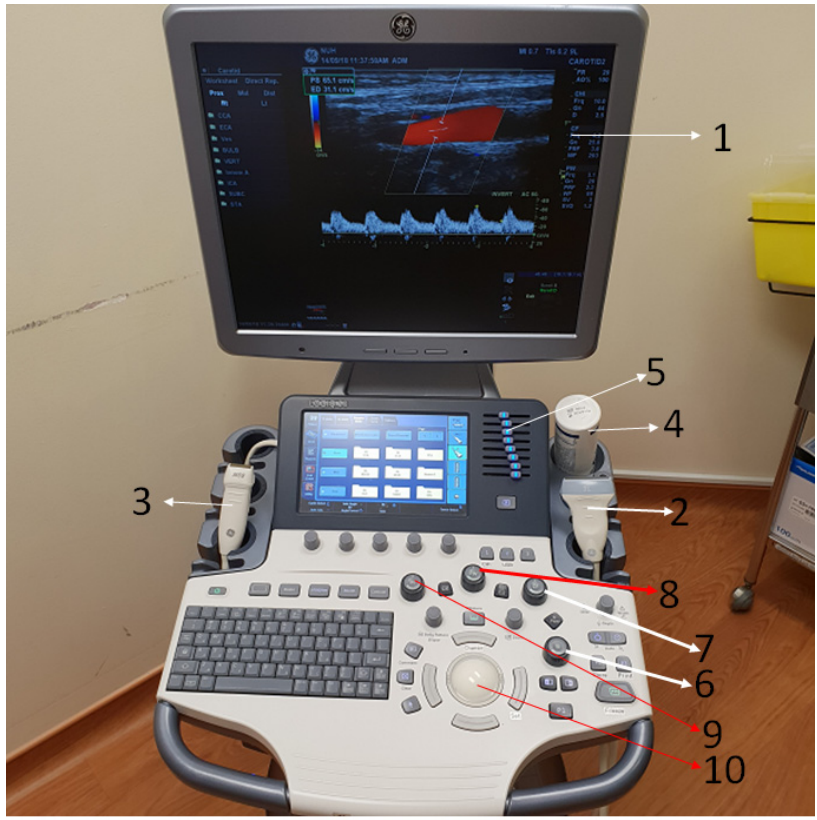

Figure 7. The basic appearance of a cervical duplex machine. Some of the most important components are:

1. Screen. This is just like the screen of modern computers. The method of display of information on the duplex scanner is fast Fourier transform (FFT).
2. Longitudinal ultrasound transducer (frequency 9-MHz) is used for cervical duplex sonography.
3. Spectral ultrasound transducer (frequency 2-MHz). For transcranial color-coded duplex (TCCD) sonography.
4. Ultrasound coupling gel bottle.
5. Time gain compensation (TGC). These knobs move horizontally for adjusting the gain at various depths.
6. Knob for Brightness-mode (B-mode) imaging. B-mode is also called grey-scale imaging. This is the most important mode for imaging of the tissues

under the transducer. This knob is rotated to increase or decrease the gain (brightness).

7. Knob for color-flow imaging (often written as CF). Once the B-mode imaging is completed, this knob is pressed to obtain the flow in a blood vessel. This button can also be rotated to adjust the color gain.
8. PW knob. This is the knob for pulsed-wave Doppler. When pressed, it helps in obtaining the spectral Doppler flow from the area of interest in a blood vessel.
9. M-Mode knob. This initiates the Motion-mode of ultrasound imaging. This mode is not used in cervical duplex imaging. This is of use during echocardiography.
10. Track ball. This ball is similar to those in laptop track-pads. It helps in moving the cursor or image to the desired frame.

Basic Operation of the Transcranial Doppler Machine

Appearance of a commercially available TCD machine is shown in figure 8.

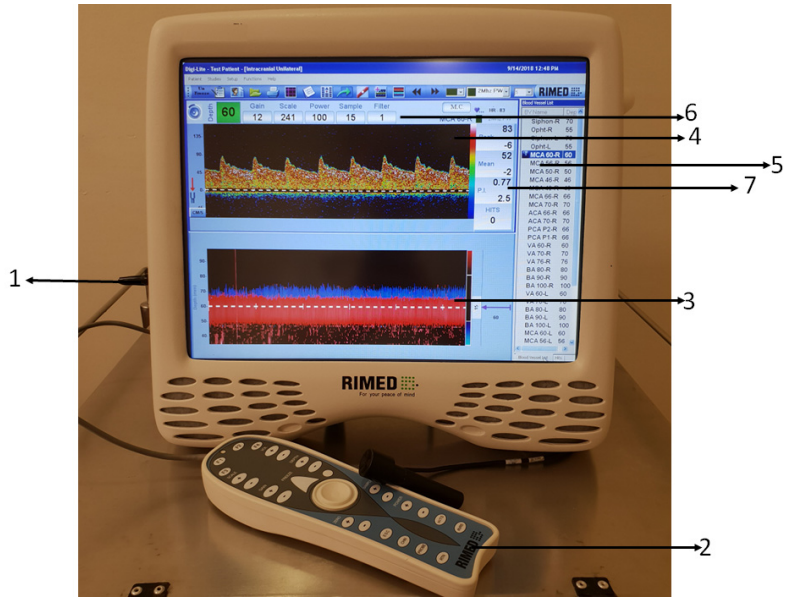

Figure 8. TCD machine. Most of the current machines have touch screens, and various parameters may be adjusted on the screen. The commonly used buttons on the machine are:

1. TCD probe. It emits 2-MHz pulsed wave ultrasound waves.
2. Remote control keyboard. It is provided in all machines since the screen may be far away from the operator to touch the screen for various adjustments. All buttons on the screen are duplicated on the remote control.
3. M-mode on the screen. It shows flow in all arteries that fall in the path of the ultrasound beam. M-mode is color coded in TCD machines where red indicates flow toward the probe while blue denotes flow away from the transducer.
4. Spectral Doppler. It shows the flow spectra from a particular depth of insonation.
5. This window shows the scanning protocol. Names of various intracranial arterial segments with their respective depths appear here.
6. This panel shows the settings of the machine for a particular frame. It shows (from left to right): depth in mm, gain in dB, scale, power, and sample volume (SV) in mm. In this frame, the spectral Doppler represents the strongest signal from a depth range of 60 ± half of SV. This means that the flow spectra shown here are the strongest signal obtained from a depth range of 52.5–67.5 mm.

Various protocols may be stored in the TCD machines. The appropriate protocol may be activated when needed.

TRANSCRANIAL DOPPLER EXAMINATION

ANNABELLE LAO-REYES, JOSE C. NAVARRO
AND VIJAY K. SHARMA

Introduction

The circle of Willis at the middle and posterior cranial fossa affords the examination of the proximal blood vessels of the cerebral circulation (figure 1). Several studies have established the utility of the transcranial Doppler (TCD) in diagnosing vascular diseases of the brain. It is portable, reliable, inexpensive, and reproducible, making it a suitable tool for bedside examination. TCD examinations broaden the ability of physicians for rapid determination of pathophysiologic mechanism of cerebral ischemia. It aids in monitoring reperfusion and early arterial re-occlusion in acute ischemic stroke patients. The accuracy of TCD has been compared with angiography (digital subtraction angiography, magnetic resonance angiography as well as computed tomographic angiography), with a reliability rate that ranges from good to excellent.

A. Machine Setup and Steps in Performing TCD Examination

TCD examination relies on the presence of an adequate temporal bone window. However, insonation of some intracranial vessels can be performed adequately through the foraminal and orbital windows. During the routine TCD examination, the machine is set to maximum power of 100 percent (except orbital window where the power is reduced to 10%) and a sample volume of 10mm. Nowadays, modern TCD machines are equipped with an M-mode multi-depth display for faster vessel identification. Additionally, the machine settings are adjusted to increase the gate if no window is detected (figure 2). If the transtemporal insonation at full power yields good echogenic spectra, the gate size and power should be reduced to minimize patients' exposure to ultrasound energy ("as low as reasonably achievable," or ALARA). Low (at 10

percent) power should be used when TCD insonation is performed via the orbital window, burr holes, or the fontanels in children.

Initially, the zero line is placed in the middle of the screen in order to display the bidirectional signals. If the velocities are high, increase the scale to avoid aliasing. This can be achieved by moving the baseline up or down also. To optimize the weaker high velocity signals, increase the gain settings with a slower sweep speed. For weaker signals, check the accuracy of the automated readings with the envelope or waveform follower. Manual cursor measurements should be performed if an erroneous envelope tracing is noted (See also chapter 16, "Pitfalls in Neurosonology").

During the spectral TCD examination, the sonographers should be able to:

1. Follow the course of blood flow for each major branch of the circle of Willis ("go with the flow").
2. Identify, optimize, and store spectral waveforms at two or more key points per artery; MCA signals may also be stored as proximal, mid, and distal; VA signals may be stored at 40–50 and 60–70 mm, and BA signals can be stored at proximal, mid, and distal segments. Note the variability of velocities in these segments.
3. Identify, optimize, and store any abnormal or unusual waveforms or signals.
4. Measure the highest velocity at each key point.

B. Windows for TCD Insonation/Blood Vessels

Transcranial Doppler Windows and Probe Position

Acoustic windows are areas in the skull where the bone is relatively thinner and permits sufficient penetration of the ultrasound. The four commonly employed acoustic windows in adults are: temporal, orbital, sub-occipital or foraminal, and submandibular. Through the transtemporal window, the flow velocities in middle cerebral (MCA), anterior cerebral (ACA), posterior cerebral (PCA), and posterior communicating (PCOM) artery are obtained. The ophthalmic artery (OA) and internal carotid artery (ICA) siphons are insonated through the transorbital window. The natural defect between the occipital bone and atlas vertebra forms the sub-occipital window that allows insonation of the vertebral (VA) and basilar

(BA) arteries. The BA can also be evaluated through the transforaminal approach. Extracranial ICA is insonated at the neck area via the submandibular approach (figures 3A–D).

Transtemporal Insonation

Place the 2-MHz TCD ultrasound transducer over the temporal area just above the zygomatic arch in front of the tragus of the ear and orient the transducer slightly upward and anteriorly (figure 3A). In power motion Doppler (PMD) mode, adjust the probe where the screen is filled with color signals between the depths of 30 and 80 mm. A red signal (toward the probe) between 40 and 65 mm represents the flow in the ipsilateral MCA, while the blue signal between 65 and 80 mm represents the flow from the ipsilateral ACA. In patients with good windows and favorable anatomy, a red signal beyond 80 mm represents flow in the contralateral A1 ACA segment.

The MI MCA stem usually lies at depths of 40–65 mm and is dependent on the size of the patients' head. It bifurcates into two divisions at a depth of 40–45 mm. Flow signals from the two M2 MCA branches are obtained by orientating the probe and optimizing the signal (figure 4A).

The ICA bifurcation is commonly observed at about 65 mm (range is 58–70 mm in adults). A bidirectional signal obtained at 60–70 mm represents ICA bifurcation. The ACA flow is usually away from the probe (blue signal with Doppler spectra below the baseline; see figures 4B and 4C).

After signals from the MCA and ACA have been obtained, the ultrasound probe is slowly orientated posteriorly by 10–30 degrees. Usually, there is a flow gap followed by flow signals from the PCA. Flow signals directed toward the probe represents P1 PCA, while those away from the flow arise from the P2 segment of the PCA (figure 4D); both segments are visualized at depths of 55–70 mm and are dependent on the probe orientation. An absence of the flow gap while moving the transducer posteriorly after the MCA/ACA evaluation usually represents flow signals from the PCOM.

Transorbital Insonation

Although no harmful effects have been reported with diagnostic TCD, the power output is reduced to 10 percent (or less than 17 mW/cm²) when the transorbital acoustic window is employed to evaluate the ophthalmic artery and the ICA siphon. The transducer is placed gently over the eyelid and it is angled slightly medial and upward. Flow signals at a depth of less than 60 mm, with a higher resistance pattern and moving toward the probe, represent the ophthalmic artery (figures 3B and 4G).

The sample volume has to be moved beyond a 60-mm depth to obtain signals from the ICA siphon. As the ICA siphon is a curved artery, the flow signals may be directed toward or away from the probe. Bidirectional signals may be obtained in some cases if the genu of the ICA siphon is insonated (figure 4H).

Suboccipital Insonation

It is convenient to turn the patient to one side and place the transducer just below and medial to the mastoid process. The probe is directed slightly medially and more horizontally toward the bridge of the nose or contralateral eye. This orientation will permit the technician to obtain flow signals from the ipsilateral VA between the depths of 50–75 mm. The flow signals are always moving away from the probe (figures 3C and 4E).

The BA may be insonated through the sub-occipital window by "going with the flow" in the ipsilateral VA by turning the probe slightly upward and medially from the depths of 75–110 mm. The BA flow signals may also be obtained through the transforaminal window by placing the transducer just below the occipital protuberance and orientating it toward the nasal bridge. Similar to vertebral arteries, the flow from the BA moves away from the probe (figures 3C and 4F).

Submandibular Window (Figure 3D)

In monitoring vasospasm after a subarachnoid hemorrhage, information regarding blood flow velocity from the extracranial internal carotid artery (eICA) should be obtained. Insonate the eICA at the neck at the level of the angle of the jaw with probe directed upward toward the head. Waveforms acquired will be moving away from the probe. The recorded

velocity is utilized to compute for the Lindergaard ratio for the diagnosis of a vasospasm.

Normal Spectral Waveform (See also chapter 3)

The normal spectral waveform shows a sharp systolic upstroke and stepwise deceleration with positive end-diastolic flow. The variables noted on typical TCD spectra are:

Peak systolic velocity (PSV in cm per second)

This is the first peak on a TCD waveform from each cardiac cycle. A rapid upstroke represents the absence of a severe stenotic lesion between the insonated intracranial arterial segment and the heart.

End-diastolic velocity (EDV in cm per second)

The end-diastolic flow velocity (EDV) lies between 20 and 50 percent of the peak systolic velocity (PSV) values, indicating a low resistance intracranial arterial flow pattern, which is seen in all major intracranial arteries.

Mean flow velocity (MFV in cm per second)

The mean flow velocity is calculated as EDV plus one-third of the difference between PSV and EDV. The MCA should have the highest MFV among all major intracranial arteries. For normal values of mean flow velocities, see table 1.

Pulsatility index (PI)

Flow resistance is usually assessed by PI, calculated by subtracting EDV from PSV and dividing the difference by MFV. This is the most frequently used TCD parameter to determine the flow resistance. The PI is independent of the angle of insonation, has no unit, and, if the value is more than 1.2, represents high-resistance blood flow.

Resistance index (RI)

The RI is another TCD parameter sometimes used to assess the flow resistance. It represents flow resistance distal to the site of insonation. RI is calculated by subtracting EDV from PSV and dividing the difference by PSV. Any value below 0.75 is normal.

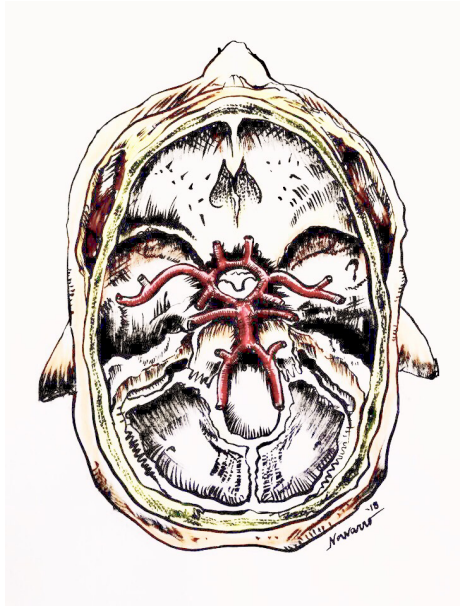

Figure 1. Circle of Willis at the base of the skull

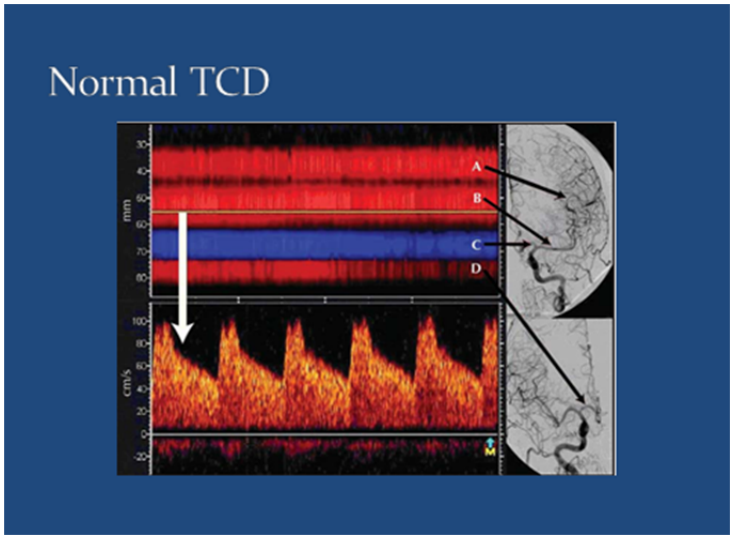

Figure 2. M-mode and normal waveforms