Practice Standards

Practice Standards for Transcranial Doppler Ultrasound: Part I—Test Performance

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ABSTRACT

Indications for the clinical use of transcranial Doppler (TCD) continue to expand while scanning protocols and quality of reporting vary between institutions. Based on literature analysis and extensive personal experience, an international expert panel started the development of guidelines for TCD performance, interpretation, and competence. The first part describes complete diagnostic spectral TCD examination for patients with cerebrovascular diseases. Cranial temporal bone windows are used for the detection of the middle cerebral arteries (MCA), anterior cerebral arteries (ACA), posterior cerebral arteries (PCA), C1 segment of the internal carotid arteries (ICA), and collateralization of flow via the anterior (AComA) and posterior (PComA) communicating arteries; orbital windows—for the ophthalmic artery (OA) and ICA siphon; the foraminal window—for the terminal vertebral (VA) and basilar (BA) arteries. Although there is a significant individual variability of the circle of Willis with and without disease, the complete diagnostic TCD examination should include bilateral assessment of the M2 (arbitrarily located at 30-40 mm depth), M1 (40-65 mm) MCA [with M1 MCA mid-point at 50 mm (range 45-55 mm), average length 16 mm (range 5-24 mm), A1 ACA (60-75 mm), C1 ICA (60-70 mm), P1-P2 PCA (average depth 63 mm (range 55-75 mm), AComA (70-80 mm), PComA (58-65 mm), OA (40-50 mm), ICA siphons (55-65 mm), terminal VA (40-75 mm), proximal (75-80), mid (80-90 mm), and distal (90-110 mm) BA]. The distal ICA on the neck (40-60 mm) can be located via submandibular windows to calculate the VMCA/VICA index, or the Lindegaard ratio for vasospasm grading after subarachnoid hemorrhage. Performance goals of diagnostic TCD are to detect and optimize arterial segment-specific spectral waveforms, determine flow direction, measure cerebral blood flow velocities and flow pulsatility in the above-mentioned arteries. These practice standards will assist laboratory accreditation processes by providing a standard scanning protocol with transducer positioning and orientation, depth selection and vessel identification for

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ultrasound devices equipped with spectral Doppler and power motion Doppler.

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Introduction

Since the invention of transcranial Doppler (TCD),[1] indications for its clinical use are constantly expanding.[2-5] Scanning protocols, numbers of vessels, depth ranges for routine evaluation as well as reporting of TCD examinations vary between institutions. Given the emphasis on accreditation of vascular laboratories,[6] there is a need for standardization of scanning and interpretation processes. We initiated the development of series of standards and guidelines by experts in transcranial Doppler and members of the American Society of Neuroimaging Practice Guidelines Committee as well as international neurosonological organizations. The first part presents practice standards recommended by this panel of experts for performance of the complete diagnostic spectral TCD examination in patients with cerebrovascular diseases.

Complete Diagnostic TCD Examination Technique

Rune Aaslid introduced a single gate spectral TCD[1] to nonivasively assess cerebral hemodynamics using the following windows for insonation (Fig 1A and B): temporal, orbital, foraminal, and submandibular.[2] Complete TCD examination encompasses not only bilateral assessment of cerebral vasculature but also utilization of the 4 cranial insonation windows to detect flow in the anterior and posterior circulation vessels.

The transtemporal approach is used to detect flow signals from the middle cerebral arteries (MCA), anterior cerebral arteries (ACA), posterior cerebral arteries (PCA), terminal internal carotid arteries (TICA), or C1 ICA segment.[1-5] The transorbital approach is used to insonate the ophthalmic artery (OA) and internal carotid artery (ICA) siphon. The transforaminal approach allows insonation of the terminal VA and BA arteries through the foramen magnum.

Cerebral hemodynamics should be viewed as a closely inter-dependent system. Although the section below provides depth ranges, it should be noted that the presence of morphological segments and their flow velocities and pulsatility might change due to anatomic variations or the presence of disease in the circle of Willis and elsewhere.

Complete diagnostic TCD examination in patients with symptoms of cerebral ischemia or at risk of stroke as well as variety of other conditions such as seen in the neuro-intensive care and chronic diseases, ie, dementia, should include bilateral assessment of the M2 (arbitrary depth range 30-40 mm), M1 (40-65 mm) MCA, A1 ACA (60-75 mm), C1 ICA (60-70 mm), P1-P2 PCA segments (55-75 mm), AComA (70-80 mm), PComA (58-65 mm), OA (40-50 mm), ICA siphons (55-65 mm), terminal VA (40-75 mm), proximal (75-80 mm), mid (80-90 mm), and distal (90-105 mm) BA. Although it was not considered mandatory to expand TCD examination to branches such as M2 MCA, these guidelines make an emphasis on performing complete examination whenever diagnostic (not limited) TCD is ordered. Note that depths of insonation vary with the size of the skull and individual anatomy, and the abovementioned segments may overlap, or located deeper than stated, ie, proximal BA could be found at 85 mm, etc.

Submandibular windows are used in patients with subarachnoid hemorrhage to measure flow velocity in the distal ICA (40-60 mm) proximal to its entry into the skull to calculate the VMCA/VICA index, or the Lindegaard ratio.[7] This ratio is prone to variability since a small decrease in the ICA velocity may greatly overestimate the degree of vasospasm.

To shorten the time necessary to find the window and to identify different arterial segments with the spectral TCD display, examination can begin with the maximum power and large gate settings (ie, power 100% achievable for a given depth but not exceeding 720 mW, gate or sample volume of 10-15 mm) for the transtemporal and foraminal approaches. Although this recommendation seemingly violates the rule of using ultrasound power as low as reasonably achievable (ALARA), it allows to shorten the time necessary to find cranial insonation windows particularly in older patients and to complete examination faster, thus reducing the overall patient exposure to ultrasound energy. Sonographers may prefer to start with a Motion-mode multidepth display or a spectral gate of smaller 5-10 mm length that reduce uncertainty in vessel identification, and increase the gate if no window is found at the beginning of the examination with a smaller gate. If transtemporal insonation at full power yields easily obtainable and highly echogenic spectra, the gate size and power should

be reduced to minimize patient exposure to ultrasound energy. Low (10%) power should be used when TCD insonation is performed via the orbital window burr holes, or fontanel.

For a typical diagnostic TCD examination, use a fast 3-5 seconds sweep speed that allows seeing details of the waveform and spectrum that improve interpretation (Fig 1C). The zero line is placed at the middle of the screen so bidirectional signals can be displayed. If velocities are high, the scale will need to be increased to avoid aliasing, which may require the baseline to be lowered. Use the gain settings to keep background noise at a minimum but present. If insonation window is limited due to excessive signal attenuation, ie, by the thickness of the temporal bone, longer duration sweeps are preferable since these provide additional time to ultrasonographer to select transducer position and make adjustments to visualize and optimize the Doppler spectrum. In case of weak high velocity signals, the sonographer can increase the gain settings with very slow sweep speed to visualize the highest Doppler frequencies in the waveform. Optimize waveforms to avoid aliasing and keep background noise at minimum using gain settings. Double check accuracy of automated readings with the envelope or waveform follower, and use manual cursor measurements if a weak signal is detected or erroneous envelope tracings are suspected.

During spectral TCD examination, sonographers should:[2,6,8,9]

1. Follow the course of blood flow in each major branch of the circle of Willis.
2. Identify, optimize, and store spectral waveforms at least at 2 key points per artery (Fig 1D, F, and G); MCA signals may also be stored as proximal, mid, and distal; VA

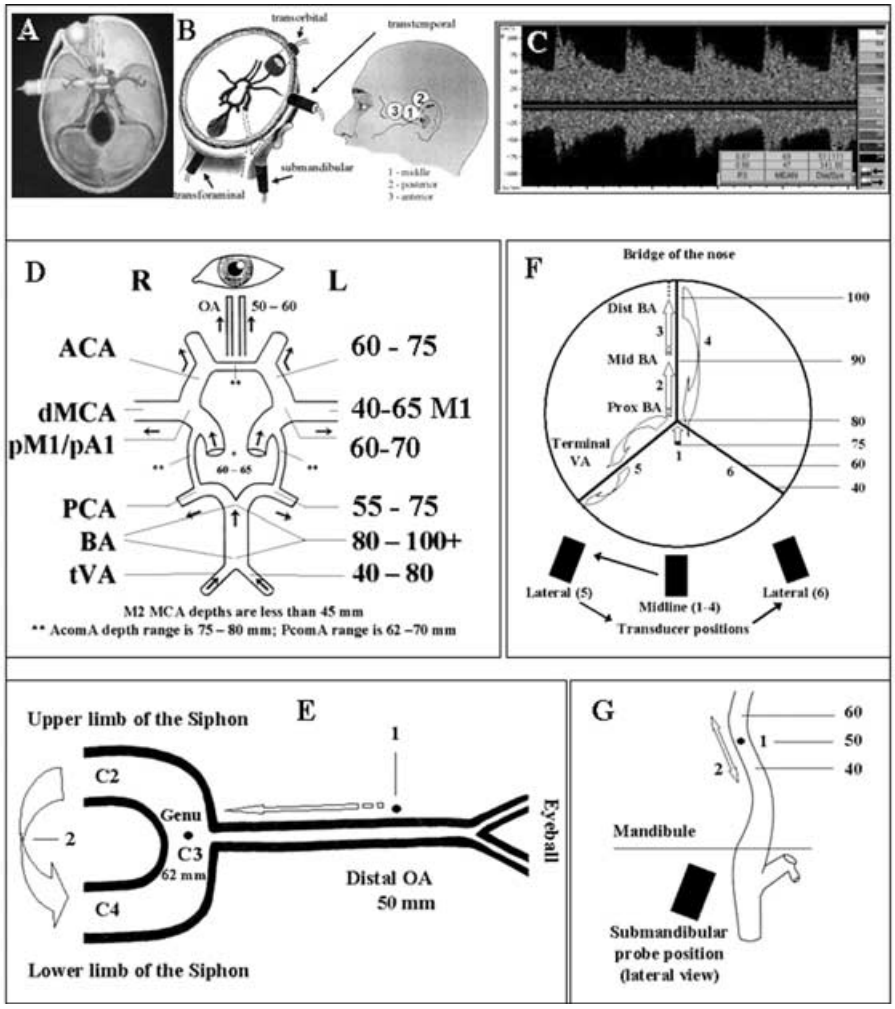

Fig 1. Windows for TCD examination, key arterial segments for complete assessment, and depth ranges for average sized adults. Solid arrows placed alongside the vessels indicate normal arterial flow direction. Solid arrows that originate at transducer drawings (F) indicate probe movement and positioning over the foraminal window that is shown in (B). Boxed arrows indicate sample volume placement along the vessels with changing depth of insonation.

signals may be stored at 40-50 and 60-70 mm, and BA signals can be stored as proximal, mid, and distal given the length and variability of velocities in these segments.
3. Identify, optimize, and store any abnormal or unusual waveforms or signals.
4. Measure the highest velocity signals at each key point.

Note that the common carotid (CCA) and vertebral artery vibration or compression tests may be performed to identify intracranial vessels. CCA compression, which is not routinely used in United States, may only be performed after CCA atheromas were excluded with direct vessel imaging since it poses a small risk of stroke.

The following steps and vessel identification criteria were adopted from several original reports and validation studies of TCD.[1,2,8,10-14] Depth ranges and flow direction are also applicable to spectral examinations guided by power motion Doppler[15] or transcranial duplex technology.[16-23]

Temporal Insonation Steps (Fig 1A, B, and D)

Step 1: Set the depth at 50 mm (mid-point of the M1 MCA segment was established at approximately 50 mm depth[13]).

Place the probe above zygomatic arch and aim it slightly upwards and anterior to the contralateral ear/window. Note that with posterior temporal window, the angulation of the probe may be even more anterior to avoid P1 PCA at the beginning of examination.

Find any flow signal (window), and avoid straight-in, downward, or too posterior transducer angulation.

Find a flow signal directed towards the probe, which resembles MCA flow. A normal MCA flow is a low resistance waveform (Fig 1C) similar to the ICA flow pattern.

By decreasing the depth, follow the signal to the distal M1 key-point of insonation without losing the signal. Often, a slight adjustment of the probe angulation is needed. Distal MCA is located more upward or anteriorly, proximal MCA is found at more "straight-in" angulation of the transducer at 90° angle against the temporal bone.

Store the highest velocity signals in the distal MCA at 30-40 mm. If bidirectional signals are found, store the highest velocity signal in each direction (distal M1–proximal M2 branches).

Step 2: Follow the signals until they disappear at shallow 30 mm depths.

Expect M2 MCA segments to have lower velocities than the M1 MCA.

Store any abnormal signal such as (but not limited to) the high velocity, high resistance waveforms, signs of turbulence, very low resistance, and delayed systolic flow acceleration.

Return to the distal M1 MCA signal.

Step 3: Follow the M1 MCA stem to its middle (45-55 mm) and the origin at 60-65 mm depths dependently on the size of adult patient skull. Pay attention to the sound and velocity changes since insonation of the terminal ICA is also possible at these depths. Keep in mind that M1 MCA is the continuation of the C1 ICA segment. Store the highest velocity signal in the proximal MCA. Proximal MCA signals usually lead to the ICA bifurcation. ICA bifurcation can be seen at a range of 51-65 mm depths[24] that will depend on the gate of insonation. Store ICA bifurcation signals at 60-65 mm to obtain both proximal M1 MCA and proximal A1 ACA signals. Store bidirectional signals from the bifurcation (M1/A1) if using a large gate of insonation–this becomes an "anchor" for other vessel identification.

Step 4: Follow the distal A1 ACA signal in its entire length, usually to 70-75 mm depths (A1 ACA has average length 13.5 mm, range 8-18.5 mm), and may end in a horizontal portion of the A2 ACA segment that could not be reliably distinguished from A1 with a nonimaging Doppler). Store the distal A1 ACA signal at 70 mm.

Step 5: Follow the distal A1 ACA signal to the midline depth range (75-80 mm). The A1 ACA signal may disappear or a bidirectional signal may appear at the midline depth with the flow directed towards the probe being contralateral ACA. Although insonation of both ACAs at midline depths may reveal anterior-crossfilling flow patterns via the anterior communicating artery,[25] differentiation of AComA flow from neighboring ACAs is virtually impossible since the insonation gate is always larger that the AComA itself, and covers both A1 ACAs and AComA.[25] Finally, multiple ACommAs can be present connecting A1 and A2 ACAs.

Store any abnormal signals.

Return to the ICA bifurcation at 60-65 mm.

Step 6: From the ICA bifurcation, aim transduce inferiorly and find the terminal ICA signal at 60-65 mm. If the probe is angled inferior and anterior to the ICA bifurcation at 60-70 mm depths, the distal part of the supraclinoid siphon can be found through the temporal window.[26] Note that TICA signal may appear blunted due to a poor angle of insonation.

Store any abnormal signal.

Return to the ICA bifurcation at 60-65 mm.

Step 7: Set the depth at 62 mm and slowly turn the transducer posteriorly by 10-30°. Usually there is a flow gap between the ICA bifurcation and the PCA signals. Find PCA signals directed towards (P1/proximal P2) and away (a more distal aspect of P2) from the probe at a depth range of 55-75 mm. Keep in mind that P1 PCA originates from the top-of-the-BA and can be found at deeper depths than P2 PCA if transducer is located in the

posterior aspect of the temporal window. Collateralization of flow via PComA can be found with these depths and transducer angulation.[25]

Store the P1 or P2 PCA signals with the highest velocity.

Orbital Insonation Steps (Fig 1E)

Step 1: Decrease power to the minimum (17 mW) or 10%.

Set the depth at 50 mm, place the transducer over eyelid and angle it slightly medially.

Determine flow pulsatility and direction in the distal ophthalmic artery.

Store the optimized distal OA signals (depth range 40-50 mm).

Step 2: Increase the depth to 55-65 mm and find the ICA siphon flow signals.

The siphon signals are usually located medially in the orbital window.

Store bidirectional signals or the highest velocity signals at 60-62 mm (C3 or the siphon genu). Note that C2-C4 segments may be sampled separately with good orbital windows.

Avoid too deep insonation and upward angulation of the transducer since good orbital windows may yield detection of the ACA flow and other intracranial vessels.

If only unidirectional signals are obtainable, store signals directed towards (C4 or the lower limb of the siphon) and away (C2 or the upper limb) from the probe.

In case of absent temporal windows, insonation via orbits can be expanded to locate intracranial signals. Note that ACA's and ICA bifurcations can be detected, however, vessel identification is less certain and may require carotid oscillation or compression tests. This approach can be used to localize abnormally high intracranial velocities but the stenosis or collateral localization will be less certain.

Foraminal Insonation Steps (Fig 1F)

Step 1: Set the system back to full power.

Place the transducer at midline an inch below the edge of the skull and aim it at the bridge of the nose.

Set the depth at 75 mm (presumed location of both terminal VA's and proximal BA).

Identify a flow signal directed away from the probe, ie, find the window.

This signal can be arbitrarily assigned to the terminal VA's (slightly lateral probe angulation) or the proximal BA (medial and slightly upward angulation).

Increasing the depth, follow the flow directed away from the probe. This depth increase presumably moves the beam towards the proximal BA in most adults.

Store the proximal BA signal arbitrarily assigned to the depth of 80 mm.

Step 2: Follow the BA artery to 90 mm (mid-BA segment).

To switch from the proximal to mid- and distal aspects of the BA, slightly push the transducer caudal on the neck but tilt it upwards since the distal BA is located more cephalad relative to the proximal vessels.

Bidirectional signals may be found at various depths with a low resistance flow in the cerebellar arteries directed towards the probe.

Store any abnormal signals.

Step 3: Follow the distal BA segment to the depth of 100-105 mm until it disappears or is replaced by the anterior circulation signals.

Store the highest velocity signal obtained at the most distal depth of the BA insonation.

Step 4: Follow the stem of the BA backwards while decreasing the depth of insonation to 80 mm and confirm previous findings.

Step 5: Place the probe about an inch laterally to the midline and aim towards the bridge of the nose or slightly towards the contralateral eye.

Find the VA flow signal directed away from the probe.

Follow the course of the terminal VA segment intracranially from 75 mm to 40 mm.

Store the VA signals at 60 mm or at the depth of the highest velocity signal. Bidirectional signals may be found at various depths with a low resistance flow in the posterior inferior cerebellar arteries directed towards the probe. Also, low velocity/low pulsatility venous flows can be detected during suboccipital insonation.

Step 6: Place the probe on the contralateral side an inch off the midline position.

Repeat the VA examination steps for the contralateral vessel from 80 to 40 mm.

Store the VA signals at 60 mm or at the depth of the highest velocity signal.

Submandibular Insonation Steps (Fig 1G)

Step 1: Place the probe laterally under the jaw anterior and medial to the sterno-cleido-mastoid muscle. Aim the transducer upwards and slightly medially.

Set the depth at 50 mm.

Find a low resistance flow directed away from the probe.

Step 2: Increase the depth from 50 to 60 mm and decrease to 40 mm.

Store the distal ICA signal at the depth that shows the highest velocity signal.

At a shallow depth, perform the temporal artery tap to differentiate with the external carotid artery flow signals.

Practical Advice

1. Avoid too anterior or too posterior, or "straight in" angulation of the probe at the beginning of the transtemporal examination.
2. Do not settle on the first signal obtained. Always keep searching for higher velocity signals that may not necessarily be the strongest in terms of signal intensity.
3. Once the highest signal is found, avoid losing signals when changing the depth of insonation; follow the course of the arteries ("go with the flow") by slightly changing angulation of the probe over the same window whenever possible. Remember the normal depth ranges (Fig 1D) and flow direction for the arteries of the circle of Willis in an adult patient.
4. Try not to take the probe off the skull until investigation of all segments through that window is completed.
5. Memorize transducer position and angulation if patient is restless or insonation is being interrupted.
6. Use insonation across midline to locate contralateral MCA/ACA signals if 1 temporal window is suboptimal, absent, or not accessible.* (see footnote)
7. Do not overgain the signals unless necessary (background should contain no or minimal amount of noise signals if the flow spectrum is easily detectable).
8. In case of weak signals, increase sample volume, decrease the sweep speed, increase gain to "boost" the signal and apply manual measurements.
9. Routinely perform complete examinations, document mean flow velocities, pulsatility indices and flow direction in all major arteries (Fig 1D), and double check missing arterial segments. Pulsatility index is affected by the heart rate that needs to be documented if follow-up studies are thought in the future. Missing arterial segments on TCD do not necessarily indicate arterial occlusion.
10. Remember that vessel identification is operator dependent. Gain experience from studying normal individuals and patients with angiographically documented arterial pathology.
11. Consistently apply the standard insonation protocol for TCD examinations. Use notes to document information pertinent to interpretation.

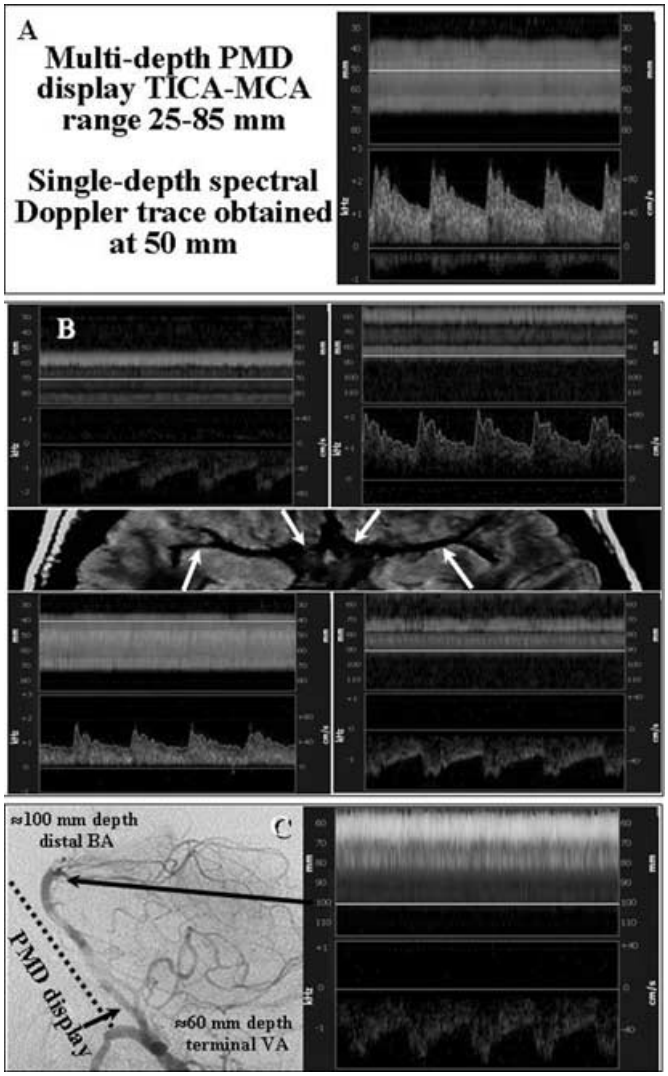

Fig 2. Power motion Doppler display as a window finding tool and a guide to a complete spectral Doppler examination.

Ultrasound window finding and vessel identification can be aided with transcranial power motion mode Doppler (PMD) that was invented by Moehring and Spencer.[15] PMD, or M-mode, simultaneously displays flow intensity and direction over several centimeters of intracranial space (Fig 2A). An advantage offered by this mode of insonation is to display all flow signals obtainable at a given position and direction of the transducer (Fig 2B and C). The promise of PMD is to make transcranial Doppler (TCD) examination easier even for an inexperienced person since it takes a long time to acquire the skills to find windows of insonation with a single channel spectral TCD.[15] Since PMD provides multi-depth information, the search for a window of insonation is not dependent on a single depth for the spectral analysis. Therefore, sonographers can simultaneously assess color-coded flow appearance at multiple depths on PMD display and choose the aspect of insonation window that yields best alignment with the target vessel(s) (Fig 2). PMD real time display serves as a window-finding tool and a guide for more complete spectral analysis.[27] The depths of spectral analysis are identified by the yellow line placed across PMD displays in Figure 2. Although PMD display may contain diagnostic signatures of flow disturbance,[27] it cannot substitute the spectral analysis for diagnostic TCD

*Insonation across midline can be difficult without imaging. You can measure the diameter of the patient skull to determine the mid-line depth. In most adults, midline is located between 70-80 mm. Once you cross the midline, the vessel identification becomes reversed: contralateral A1 ACA is directed towards the probe (range 75-85 mm), while others are directed away from the probe: M1 MCA (range 85-105+ mm), TICA (80-85 mm), and P1/P2 PCA (75-83 mm). The top of the BA segment at midline depths and the very proximal contralateral P1 PCA can be directed towards the probe from the transtemporal window.

Table 1. Normal Depth, Direction, and Mean Flow Velocities at Assumed Zero Degree Angle of Insonation of the Arteries of the Circle of Willis

Artery	Depth (mm)	Direction	Children*	Adults
M2 MCA	30-40	Bidirectional	<170 cm/second	30-80 cm/second
M1 MCA	40-65	Towards	<170 cm/second	30-80 cm/second
A1 ACA	60-75	Away	<150 cm/second	30-80 cm/second
A1-A2 ACA**	45-70	Towards	N/A	20-80 cm/second
ICA siphon	58-65	Bidirectional	<130 cm/second	20-70 cm/second
OA	40-50	Towards	Variable	Variable
PCA	55-75	Bidirectional	<100 cm/second	20-60 cm/second
BA	80-105	Away	<100 cm/second	20-60 cm/second
VA	40-75	Away	<80 cm/second	20-50 cm/second

*Values are given for children with sickle cell anemia.
**A2 ACA can be found through the frontal windows in selected patients.[26]

Table 2. Expected arterial depths for different head diameters in children

Head diameter	Proximal MCA	Distal MCA	ICA Bifurcation	ACA	PCA
12 cm	30-54	30-36	50-54	50-58	40-60
13 cm	30-58	30-36	52-58	52-62	42-66
14 cm	34-62	34-40	56-64	56-68	46-70

Depths of insonation are given for the ipsilateral transtemporal window of insonation.[28,29,31,32]

interpretation. Spectral analysis of the key intracranial arterial segments has to be performed at all times possible even if PMD or color flow duplex technology is used to identify windows and vessels. Absent temporal windows should be documented in the report, and this should not preclude assessment of all other windows for TCD examination.

A report for the complete diagnostic TCD examination should contain, at a minimum:

1. date and time of the examination;
2. patient name, demographics, medical record number
3. clinical indications;
4. a description of the test that was performed;
5. a statement of the data obtained;
6. reasons for unsuccessful evaluation, ie, absent temporal windows;
7. interpretation of the ultrasound examination data;
8. a comparison with results from previous examinations, if applicable; and
9. clinical implications of this study.

Table 1 summarizes normal depth ranges in adults (Table 2 for children), flow direction, and velocity values from published studies.[10-12,14,17,18,28,29] Additionally, the frontal bone windows of insonation may allow assessment of the A1 and A2 ACA segments in select patients.[30] This approach, however, often lacks successful bone penetration and findings were not yet validated against angiography. Although it is not a required part of the diagnostic TCD examination, sonographers should be aware of this potential window and use it particularly when the A1-A2 ACA disease is suspected, ie, intracranial stenosis, vasculitis, ACA vasospasm, etc.

Subsequent parts of these series will detail specific TCD procedures, diagnostic criteria for interpretation of abnormal studies as well as competency standards for neurovascular sonographers and interpreting physicians.

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