The neurosonologists or ultrasonographers should be knowledgeable on the anatomy and the spatial relationship of intracranial vessels in order to accurately identify the insonated vessels with transcranial Doppler (TCD). As the details on the insonations, depths, machine settings, other parameters, and indications (Table 1) are available in the clinical studies,1-5 guideline, proposals for standardization,6-9 practice parameters10,11 and books,12-15 the detailed technical specifications of TCD will not be discussed.

The TCD uses low frequency (1.5–2 MHz) ultrasound which can penetrate deeply with less attenuation to study intracranial arteries through “windows” or “holes” in the skull. In order to overcome the skull which limits penetration of ultrasound, ultrasound is delivered through acoustic windows where the skull is thin or absent (Figs. 1-3). The three commonly used acoustic windows are temporal, orbital, and suboccipital windows. The temporal window through the thinnest part of the temporal bone allows the insonation of the middle cerebral artery (MCA), anterior cerebral artery (ACA), posterior cerebral artery (PCA), and terminal internal carotid artery. The orbital window can give access to the ophthalmic artery (OA) and carotid siphon of the internal carotid artery (sICA). The suboccipital window through the foramen magnum provides access to the intracranial part of the vertebral artery (VA) and basilar artery (BA) (Table 2).

The conventional or blind TCD uses dedicated pulsed-Doppler to demonstrate spectra alone. The regular ultrasound machines with the dedicated software for transcranial color Doppler (TCCD) and small-footprint phased array transducer enable neurosonologists to use B-mode and Doppler mode simultaneously for visualization of both intracranial anatomy and flows.3 One of the strengths of TCD is its non-invasiveness and availability at bed-side examination as point-of-care-ultrasound.

In order to appropriately interpret findings on TCD, the reader should understand the principles of hemodynamics including Spencer’s curve.12,16-18

The initial step of interpretation is to check whether all the insonated vascular segments are correctly identified and labelled, especially when the TCD study was performed by other ultrasonographers or neurosonologists, by carefully reviewing the depths and directions of the spectra. These should be compared with the patient’s clinical presentation and other imaging studies. The reader should be familiar with the interpretation of normal, pathologic, and abnormal intracranial hemodynamics to effectively interpret TCD findings.
of flow of each insonated segment in relation to the Doppler probe: the MCA, PCA P1, and OA flow signals are directed toward the probe and ACA; PCA P2, VA, and BA signals are directed away from the probe.

The second step is to analyze the components of a cardiac cycle of Doppler spectral waveforms to identify the systolic and diastolic components: the initiation of systole; the shape and magnitude of flow acceleration to the peak velocity; peak velocity during systole (peak systole); dicrotic notch (closure of the aortic valve indicating the initiation of diastole); end-diastolic flow velocity; and the shape and magnitude of flow deceleration after the peak systole (Table 3, Fig. 4).

The flow velocity (FV) is the key parameter. The MCA FV is the highest, the ACA is the second highest, and then the PCA FV is the lowest in the most normal patients.

The pulsatility index (PI) provides the information on the status of distal vascular system or distal vascular resistance and the normal range is between 0.6 and 1.1. The low PI suggests decreased vascular resistance such as hypercapnia or vasodilatation of distal vascular system to compensate for diminished perfusion. The decreased PI can be seen with proximal arterial stenosis. The high PI indicates increased distal vascular resistance such as increased intracranial pressure, significant stenosis or occlusion of distal vascular segments or territory supplied by the insonated vessels, stiffening of distal vessels due to aging, and small artery disease.

The flow acceleration of Doppler spectral waveforms provides the status of proximal vascular system. The delayed systolic acceleration or post-stenotic waveform indicates significantly decreased and slow flow to the insonated vascular segments due to proximal vascular stenosis or occlusion compromising perfusion.

The neurosonologists should check whether the spectral waveforms show early systolic deceleration or

| Table 1. Indications for transcranial Doppler |
|---------------------------------------------|
| Screening of children aged 2–16 years with sickle cell disease for assessing stroke risk |
| Detection and monitoring of angiographic vasospasm after spontaneous subarachnoid hemorrhage |
| Monitoring thrombolysis of intracranial artery occlusions |
| The detection of cerebral microembolic signals in a variety of cardiovascular/cerebrovascular disorders/procedures; detection of hemodynamic and embolic events that may result in perioperative stroke during and after carotid endarterectomy in settings where monitoring is felt to be necessary |
| Monitoring during surgery for hemodynamic status; vasomotor reactivity testing |
| Detection of right-to-left shunts |
| Diagnosis of intracranial occlusive disease |
| Ancillary test for confirmation or exclusion of extracranial occlusive disease |
| Confirmation of well-collateralized chronic internal carotid artery occlusions |
| Diagnosis and follow-up of internal carotid artery |
| Evaluation of hemodynamic effects of extracranial occlusive disease on intracranial blood flow velocities |
| Internal carotid artery stenosis or occlusion |
| Subclavian steal mechanism |
| Functional tests such as measuring blood flow velocity during activation of circumscribed cortical areas, light and mental stimulation of the visual cortex, etc. |
| Noninvasive ancillary tests and monitoring procedures in animal experiments |
| Monitoring during experiments in space |

**Fig. 1.** Acoustic windows. AW; anterior window, MW; middle window, PW; posterior window.
Table 2. Normal mean velocities, directions, acoustic windows of intracranial arteries

| Artery          | Window    | Depth, mm | Direction | MFV, cm/s |
|-----------------|-----------|-----------|-----------|-----------|
| MCA M1 (M2)     | Temporal  | 40–65     | ➞ ▼       | <80       |
| ACA A1          | Temporal  | 62–75     | ➞ ▼       | <80       |
| PCA             | Temporal  | 60–68     | ⇔ ▼       | <50       |
| ICA Siphon      | Orbital   | 60–64     | ⇔ ▼       | <70       |
| OA              | Orbital   | 50–62     | ➞ ▼       | Variable  |
| BA              | Suboccipital | 80–100 | ⇔ ▼       | <60       |
| VA              | Suboccipital | 45–80     | ⇔ ▼       | <50       |

MFV; mean flow velocity, MCA; middle cerebral artery, ACA; anterior cerebral artery, PCA; posterior cerebral artery, ICA; internal carotid artery, OA; ophthalmic artery, BA; basilar artery, VA; vertebral artery.

Fig. 2. Acoustic windows for blind transcranial color Doppler. (A) Temporal window. (B) Orbital window. (C) Suboccipital window.

Fig. 3. Acoustic windows for blind transcranial color Doppler. (A) Temporal window. (B) Orbital window. (C) Suboccipital window.
alternating waveforms. The early systolic deceleration or alternating waveform of VA and/or BA suggest steal phenomenon of proximal vessels. The alternating waveform of ACA indicates severe stenosis of ipsilateral extracranial arteries, either at the very proximal segment or the segment closer to the aortic arch.

Other ancillary findings of waveforms such as turbulence and musical murmur would provide additional information to better characterize the underlying pathophysiology.

After complete review of the spectral waveforms of individual vascular segments, comparison of FVs and other characteristics of flow signals between right and left intracranial vessels for any asymmetry should be done. For example, when the left MCA shows significantly increased FVs than that of right MCA, the post-stenotic waveforms at the distal left MCA segments would suggest the hemodynamically significant focal stenosis

| Table 3. Key parameters for TCD waveforms |
|------------------------------------------|
| Direction of flow in relation to the probe |
| Depth of insonation |
| Time-averaged maximum mean flow velocity |
| Peak flow velocity |
| End-diastolic velocity |
| Flow acceleration |
| Pulsatility index |

TCD; transcranial Doppler.

Table 4. Conditions and factors affecting pulsatility index

| Increased |
|-----------|
| Increased distal vascular resistance |
| Increased intracranial pressure |
| Hypocapnia |
| Occlusion or severe stenosis of distal intracranial arteries |
| Cerebral circulatory arrest |
| Advanced age |
| Small artery disease |

| Decreased |
|-----------|
| Decreased distal vascular resistance |
| Vasodilatation of distal vascular system to compensate the decreased perfusion |
| Hypercapnia |
| Hyperemia |
| Arteriovenous malformation |

Fig. 4. Doppler spectral waveforms. PW; pulse wave, MCA_R; middle cerebral artery right, PI; pulsatility index, RI; resistance index.
of the left MCA but the presence of post-stenotic waveforms in the right MCA with reversed right ACA and the normal waveforms in the proximal and distal left MCA would indicate hemodynamically significant stenosis or occlusion of right proximal ICA.

INTRACRANIAL ARTERIAL STENOSIS

Patients with stroke with severe (>70%) intracranial atherosclerotic disease are at the highest risk of stroke recurrence. TCD shows high diagnostic accuracy against computed tomography angiography (CTA) in evaluating intracranial arterial stenosis/occlusion in patients with acute ischemic stroke when TCD is performed within the short time period after CTA.37

The typical findings for intracranial artery stenosis include increased FV, turbulence at or immediately distal to the stenosis, low-frequency noise produced by non-harmonic covibrations of the vessel wall, and sometimes musical murmurs due to harmonic covibrations producing pure tones (Fig. 5).38

1. Anterior circulation

1) MCA

Most of the stenotic lesions of the basal cerebral arteries involve the M1 segment and the sICA, commonly secondary to atherosclerosis. Moyamoya disease (MMD), vasculitis, and sickle cell disease can cause intracranial arterial diseases. TCD findings compatible with stenotic lesions of the M1 segment of MCA include increased peak systolic flow velocity (PSFV) and mean flow velocity (MFV), decreased FVs in the segment distal to the stenotic lesion, spectral narrowing, and low frequency bidirectional signal during systole, arterial wall covibration, and harmonic murmur. The increased MFVs run between 80–250 cm/s (Fig. 5A, Supplementary Video 1). The sensitivity of TCD in detecting MCA lesion with >50% stenosis varies between 75% and 100%,39-43 and its specificity is greater than 86%.42,43

The absence or severe reduction of detectable signals at depths of insonation corresponding to the MCA (45 to 65 mm) in the presence of signals of the ipsilateral other basal cerebral arteries suggests MCA occlusion.

Fig. 5. Intracranial arterial stenosis. (A) Left MCA stenosis, (B) ACA stenosis, (C) BA stenosis, (D) BA stenosis with musical murmur. Lt; left, MCA; middle cerebral artery, FV; flow velocity, ACA; anterior cerebral artery, BA; basilar artery.
The MCA branch occlusion would show decreased FVs due to increased distal vascular resistance, often associated with a relatively increased FVs in the ipsilateral ACA.

In some patients with chronic MCA occlusion, TCD can show normal-appearing vascular signals in the MCA due to increased flow through collateral channels and lenticulostriate arteries and the increased FV in the ipsilateral ACA with or without reversed flow would further support the diagnosis. The FVs of the ipsilateral ICA could be normal if there is enough collateral flow via anterior cross-over or leptomeningeal collaterals.

2) ACA
TCD findings of stenotic ACA include increased PS-FVs and MFVs, spectral narrowing, low frequency bidirectional signal during systole, arterial wall covibration, and harmonic murmur (Fig. 5B, Supplementary Video 2).

3) ICA siphon
The sICA lesions could cause increased FVs (mean >65 cm/s) and symmetrical prominent low frequencies with decreased ipsilateral MCA FVs, increased FVs (mean >85 cm/s, peak 115 cm/s) of the contralateral ACA due to collateral through ACOM.44

2. Posterior circulation

The proximal PCA stenosis or occlusion would show increased FVs. BA stenosis of >50% lumen reduction would show increased PSFV (120–250 cm/s) and MFV (50–150 cm/s) and the most sensitive MFV thresholds for >70% stenosis for BA is >110 cm/s and/or PSFV >160 cm/s (Fig. 5C, D, Supplementary Videos 3, 4). However, the increased velocity of BA does not necessarily suggest BA stenosis and may be due to development of intracranial collateral through posterior communicating artery and circle of Willis secondary to large artery stenosis of the anterior circulation.45

The proximal VA stenosis can be diagnosed with extracranial Duplex ultrasound but TCD would show in-

![Fig. 6. Proximal internal carotid artery stenosis or occlusion. (A) Post-stenotic flow waveforms with delayed systolic acceleration and high diastolic flow. (B) Reversed right ACA. (C) Reversed right ophthalmic artery. (D) Post-stenotic flow waveform with delayed systolic acceleration. Rt; right, MCA; middle cerebral artery, ACA; anterior cerebral artery, FV; flow velocity, Lt; left.](http://www.j-nn.org)
increased PSFV and MFVs at the circumscribed location with poststenotic waveforms at the distal segments.

PROXIMAL INTERNAL CAROTID ARTERY STENOSIS AND OCCLUSION

There is some inverse relationship between MCA MFV (or SFV) and severity of ipsilateral ICA stenosis (ICS) (Fig. 6A, Supplementary Video 5).\textsuperscript{46-48} Almost all are diagnostically abnormal only when the ICS exceeds 70% diameter reduction and the threshold of hemodynamic significance determined by TCD is comparable with the critical stenosis determined by electromagnetic blood flow measurements.\textsuperscript{49} However, the MFV alone is not sensitive parameter for ICS. Only 45% of patients with severe carotid stenosis have detectable intracranial hemodynamic changes due to collateral channels and vasodilatation of distal vascular system: MFV can be in the normal range in spite of significant stenosis and TCD can show preserved flow pattern in spite of obvious occlusion in the proximal ICA (Supplementary Video 6).

The PI is decreased in patients with carotid stenosis because the peak SFV decreases due to decreased perfusion and the EDFV increases due to vasodilatation of distal vascular system to increase distal perfusion (Fig. 6A, Supplementary Video 5). The PI does not decrease until the severity of stenosis exceeds 80% (Fig. 6D).\textsuperscript{20}

TCD can identify collateral flow through the ACOM (Fig. 6B, Supplementary Video 7), PCOM, and OA. The presence of an OA collateral is a highly specific indicator of reduced cerebral perfusion pressure (Fig. 6C, Supplementary Video 6).

ANTERIOR CEREBRAL ARTERY HYPOPLASIA

ACA spectra should be interpreted with caution be-

![Fig. 7](image1.png) Anterior cerebral artery hypoplasia and hyperplasia. (A) Hyperplastic right ACA. (B) Hypoplastic left ACA. FV; flow velocity, PI; pulsatility index, ACA; anterior cerebral artery.

![Fig. 8](image2.png) Vertebral artery hypoplasia and hyperplasia. (A) Hypoplastic right VA. (B) Hyperplastic left VA. FV; flow velocity, VA; vertebral artery.
cause the A1 segment of ACA is hypoplastic in 10-25% of all anatomic dissections and the contralateral ACA supplies part or all of the ACA vascular territory in the opposite hemisphere via a large ACOM and two normal distal A2 segments.50-53

Low FV of ACA with normal findings of other basal cerebral arteries would indicate either hypoplasia (HP) or aplasia (AP) of ipsilateral ACA or increased distal vascular resistance such as distal ACA stenosis or occlusion (Fig. 7, Supplementary Video 8). If asymmetry index is high (>50%), HP or AP is the most likely explanation.53 When other vascular segments shows abnormal findings, the high FV of ACA would indicate either stenosis or hyperemia.

Fig. 9. Vertebral artery hypoplasia and hyperplasia. (A) Hyperplastic right VA Doppler on Duplex. (B) Larger right VA on B mode. (C) Hypoplastic left VA Doppler on Duplex. (D) Smaller left VA on B mode. (E) Hyperplastic right VA on TCD. (F) Hypoplastic left VA on TCD. FV; flow velocity, VA; vertebral artery, TCD; transcranial Doppler.
Fig. 10. High and low pulsatility indices. (A) High PI, low diastolic FV in increased intracranial pressure prior to lumbar puncture. (B) Low PI, increased diastolic FV in normalized intracranial pressure immediately after lumbar puncture. (C, D) High PI with normal FV in patient with diffuse small artery disease. PI; pulsatility index, FV; flow velocity.

Fig. 11. Parvus et tardus waveforms at (A) right MCA, (B) left MCA, (C) right PCA, (D) left PCA. TCD; transcranial Doppler, MCA; middle cerebral artery, PCA; posterior cerebral artery.
VERTEBRAL ARTERY HYPOPLASIA

Asymmetry of FV of VAs is not an uncommon finding (Fig. 8, Supplementary Video 9). The prevalence of hypoplastic vertebral artery based on MRA study in normal healthy population was 26.5%, more common on the right, and higher (35.2%) in patients with posterior circulation stroke.

Increased MFV of unilateral VA on TCD may indicate either ipsilateral stenosis or contralateral HP or AP. If other vascular segments do not show any abnormal findings, asymmetry index greater than 40% would highly suggest unilateral HP or AP. The low PSV (<50% of normal peak systolic velocity [PSV]) and PSV <0.30 m/s with slow early systolic acceleration of intracranial VA would suggest diffusely severe or localized critical intracranial VA stenosis.

Duplex ultrasound of extracranial VA would provide additional information: the relatively smaller VA diameter, low FV with increased RI, and decreased flow volume indicate hypoplastic VA (Fig. 9, Supplementary Video 10).

HIGH AND LOW PULSATILITY INDICES

The PI provides the information on the status of distal vascular system or distal vascular resistance (normal range, 0.6–1.1). The low PI suggests decreased vascular resistance such as hypercapnia or vasodilatation of distal vascular system to compensate for diminished perfusion. The high PI indicates increased distal vascular resistance such as increased intracranial pressure (Fig. 10A, B, Supplementary Videos 11, 12), significant stenosis or occlusion of distal vascular segments or territory supplied by the insonated vessels, stiffening of distal vessels due to aging, or small artery disease (Fig. 10C, D, Supplementary Video 13).

PARVUS ET TARDUS WAVEFORMS

The parvus et tardus (PeT) waveforms (increased acceleration time, decreased PSFV, delayed upstroke, and rounded waveform) suggest significant proximal vascular disease or severe valvular disease such as aortic stenosis.

The PeT waveforms in all intracranial vascular segments in both anterior and posterior circulation would indicate diffuse proximal vascular disease or severe aortic stenosis (Fig. 11, Supplementary Video 14). The PeT in right anterior circulation with ipsilateral VA would suggest innominate artery severe stenosis or occlusion.

MURMURS

Musical murmurs (MMs) are murmurs with a single frequency, producing sound suggestive of a musical tone, and the Doppler spectra show mirror-image parallel strings or bands of low to moderate frequency. MMs result from uniform and periodic vibrations of normal and abnormal cardiac structures with or without turbulent flow, a periodic shedding of vortices in
the cerebral arteries, and oscillating structures and pressure fluctuations in intracranial arterial spasm.\textsuperscript{33-36}

The presence of MMs on TCD could indicate pathologically increased blood velocities and pathological changes in the vessel walls in addition to geometrical configurations of the arteries (Fig. 12, Supplementary Videos 15, 16).\textsuperscript{36,59}

It is rare in intra and extracranial arteries (0.5% of patients with suspected cerebrovascular diseases), more common in the intracranial than extracranial arteries.\textsuperscript{59} MMs were detected about half of subarachnoid hemorrhage (SAH) patients (Fig. 13C, D, Supplementary Video 16).\textsuperscript{36} It is very rare in the peripheral and visceral vessels.\textsuperscript{60}

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{example.pdf}
\caption{Vasospasms in the patient with subarachnoid hemorrhage due to ruptured PICA aneurysm. (A) Day 3 after SAH. (B) Day 4 after SAH. (C) Day 5 after SAH. (D) Day 6 after SAH. (E) Day 7 after SAH. (F) Day 10 (post-angioplasty) after SAH. SAH; subarachnoid hemorrhage, VA; vertebral artery, mFV; mean flow velocity, PI; pulsatility index, MCA; middle cerebral artery, ACA; anterior cerebral artery, PICA; posterior inferior cerebellar artery.}
\end{figure}
Cerebral Vasospasm in Subarachnoid Hemorrhage

Vasospasm (VSP) is a major complication of SAH. Its incidence runs between 30% and 70% and the morbidity and mortality related to clinical VSP ranges from 10% to 20%. VSP is usually absent in the first 48–72 hours after SAH. It develops from day 3 to reach a peak between day 6 and 12, gradually lessening at 15–20 days (Fig. 13, Supplementary Videos 17-22, Tables 5, 6).

TCD is effective to diagnosis of cerebral VSP both in anterior and posterior circulation following SAH. TCD can detect the development of VSP days before it can become clinically apparent (days 2–5 following SAH onset) and detect progression to the severe phase of VSP.

**Table 5.** Vasospasm criteria

| Insonated vessels | Mild vasospasm MFV, cm/s | Moderate vasospasm MFV, cm/s | Severe vasospasm MFV, cm/s | Intracranial MFV/extra-cranial MFV |
|-------------------|--------------------------|-----------------------------|---------------------------|----------------------------------|
| ACA               | φ                        | MFV >50% increase from baseline in 24 hours | MFV >50% increase from baseline in 24 hours | φ                                |
| ICA (terminal)    | >120                     | >150                        | φ                         | φ                                |
| MCA               | >120                     | >150                        | >200                      | >3 mild                         |
|                   |                          |                             |                           | 3–6 moderate                     |
|                   |                          |                             |                           | >6 severe                        |
| PCA               | φ                        | >110                        | >110                      | φ                                |
| BA                | >60                      | >80                         | >115                      | >3 severe                        |
| VA                | >60                      | >80                         | >80                       | φ                                |

MFV; mean flow velocity, ACA; anterior cerebral artery, φ; variable or undefined, ICA; internal carotid artery, MCA; middle cerebral artery, PCA; posterior cerebral artery, BA; basilar artery, VA; vertebral artery.

**Table 6.** Red flags in patients with SAH for vasospasm monitoring

- Average rate of rise in FVs >20 cm/s/day between days 3 and 7 after the onset of SAH
- Rapid early increase in flow velocities ( >25%/day)
- Mean absolute rise in MCA FVs or ACA FVs of 65±5 cm/s over 24-hour period and higher MCA/ICA ratio (6±0.2)
- 50% velocity increase in daily serial examination or the presence of an asymmetry (velocity difference exceeding 50%)

SAH; subarachnoid hemorrhage, FV; flow velocity, MCA; middle cerebral artery, ACA; anterior cerebral artery, ICA; internal carotid artery.

**Table 7.** STOP study criteria for sickle cell anemia

|                      | Non-Imaging                      | Imaging                      |
|----------------------|----------------------------------|------------------------------|
| Normal               | TAMM <170 cm/s                   | TAMM of 160–184 cm/s         |
| Conditional          | TAMM >170 but <200 cm/s in the MCA and/or distal ICA, TAMM >170 in PCA or ACA | PSV of 200–250               |
| Abnormal             | TAMM ≥200 cm/s in MCA and/or terminal ICA | TAMM ≥185 cm/s               |
|                      | TAMM > 220 cm/s*                 | PSV >250 cm/s                |
| Inadequate           | Study was unable to read          | PSV >280 cm/s*               |

STOP; stroke prevention in sickle cell disease, TAMM; time-averaged mean of the maximum, MCA; middle cerebral artery, ICA; internal carotid artery, PCA; posterior cerebral artery, PSV; peak systolic velocity.

*Confirmative: 95% of having a second abnormal transcranial Doppler on repeated testing.
TCD findings include increased FVs, turbulence, and musical murmurs (Fig. 13, Supplementary Videos 17-22).  

SICKLE CELL ANEMIA

The sickle cell anemia children with time average maximum mean velocity of >200 cm/s in the distal ICA or proximal MCA had significantly increased stroke risk, 10–20 times that of the general sickle cell population of the same age. The primary prevention with transfusion decreased stroke by 90%. The patients with abnormal velocity should undergo repeated screening within the next few weeks and if the second study is also abnormal, the patients would require treatment (Table 7). Those with conditional velocity should be studied within 3–6 months, while those with normal studies can get a follow up TCD yearly. The studies should be performed per the recommended study protocol.65–71

Other abnormal findings include low FV in MCA (<70 cm/s), MCA ratio <0.5, ipsilateral ACA/MCA ratio >1.2, dampened waveform, turbulence, and musical harmonic murmurs (Fig. 14, Supplementary Video 23).

MOYAMOYA DISEASE

MMD is a cerebrovascular disease characterized by progressive stenosis or occlusion of the terminal internal carotid or middle cerebral arteries with abnormal basal collaterals with perforating branches as a main constituent.23 Because of its non-invasiveness, low cost, and high diagnostic agreement with MRA and cerebral angiography, TCD may be the preferred choice for screening,73 follow-up evaluations of different stages of MMD,74 assessment of hemodynamic changes,75 and assessment of anastomosis and its impact on hemodynamics.76

The MM blood vessels are the collaterals formed as a result of the stenosis or occlusion of the carotid bifurcation with perforating branches as a main constituent. These can be detected as multiple flow signals with low velocity and resistance on Doppler and scatters or confetti of colored dots on color Doppler next to or around proximal and/or distal MCA.77

The various findings can be detected depending on the angiographic stages of the patients72,78 (Table 8) including increased FVs in multiple basal arteries with low resistance,78 significantly decreased FVs,79 absence of flow signals in more than 2 basal arteries,80 multiple

Fig. 14. Sickle cell anemia. (A) Increased FV at right MCA. (B) Turbulence at left MCA. (C) Turbulence at right MCA. (D) Increased FV at left MCA. FV; flow velocity, MCA; middle cerebral artery.
flow signals with low velocity and resistance. The TCCD would demonstrate presence of scattered and colored dots at the base of the brain on Color Doppler with signals of low velocity and resistance index on Doppler (Fig. 15, Supplementary Video 24). The recent study on MMD with contrast-enhanced transcranial Doppler sonography (CE-TCCD) showed significant correlation between the CE-TCCD findings and the Suzuki angiographic grades and hemodynamic parameters.

MMD will be highly suspected in young adults with cerebral hemorrhage or ischemic stroke of uncertain etiology if TCD shows increased or decreased FVs of major cerebral basal arteries with multiple flow signals with low velocity and resistance on TCD and/or scattered or confetti of colored dots at the base of the brain on TCCD.

### Table 8. Moyamoya disease: angiographic stages, Doppler, and color Doppler

| Suzuki angiographic stage – MM vessels and other findings | TCD | TCCD |
|----------------------------------------------------------|-----|------|
| I. Narrowing of carotid fork | Increased FVs of CS | |
| II. Initiation of MM | Large and obscure or narrow carotid fork | Increased FVs of CS | Scattered and colored dots at the base of the brain |
| | All dilated and enlarged intracerebral main arteries | Increased FVs of MCA and ACA | |
| | Slightly formed MM vessels | Some flow signals with low FV and R | |
| III. Intensification of MM | Defection of MCA and ACA | Increased FVs of carotid siphon | Confetti of colored dots at the base of the brain |
| | MM vessels with changes in main intracerebral arteries (form of distinctly visualized cluster of the blood vessels) | Increased FVs of MCA and ACA | |
| | | Some flow signals with low FV and R around proximal and distal MCA | |
| IV. Minimization of MM | Thin ACA and MCA | Increased FVs of MCA and ACA | Diminishing confetti of colored confetti |
| | Thin and poor network | Multiple flow signals with low FV and R around proximal and distal MCA | |
| V. Reduction of the MM | Complete disappearance of the whole main arteries from ICA | Low FV with or without increased R of MCA and ACA | Some scattered and colored dots at the base of the brain |
| | Poor MM limited to the siphon | Low resistance or reversed ophthalmic arteries with low R | |
| | Increased collateral from ECA | Internalization of ECA | |
| | | Increased FV of PCOM | |
| VI. Disappearance of MM | Complete missing of circulation from ICA | Low FV with or without increased R | |
| | Maintenance of cerebral circulation only the route of ECA or of VA | Reversed OA | |
| | | Internalization of ECA | |
| | | Increased FV of PCOM | |

MM; Moyamoya, TCD; transcranial Doppler, TCCD; transcranial color Doppler, CS; carotid siphon, MCA; middle cerebral artery, ACA; anterior cerebral artery, DV; flow velocity, R; resistance, ECA; external carotid artery, PCOM; posterior communicating artery, VA; vertebral artery, OA; ophthalmic artery.

### INTRACRANIAL ALTERNATING WAVEFORMS

Alternating flow or waveforms in the ACA is rare but provides an important localizing value for the diagnosis of extracranial vascular diseases because it is associated with ipsilateral proximal stenosis in the supra-aortic arteries, either in the innominate artery or at the origin of the common carotid artery (Fig. 16, Supplementary Videos 25, 26).

### MICROEMBOLIC SIGNALS

TCD is used to detect cerebral embolization in patients with ischemic strokes, transient ischemic attacks (TIAs), or asymptomatic high-grade ICA stenosis. The detection of emboli or microembolic signal (MES) is helpful to establish the diagnosis and change management strategy. The presence of emboli on TCD distal
to a high-grade asymptomatic ICA stenosis identifies patients at higher risk of first-ever stroke (Fig. 17, Supplementary Videos 27, 28).84,85 TCD “bubble” test can be performed on patients with ischemic stroke and TIAs due to possible paradoxical embolism to detect right-to-left shunt.

The MES identification for the clinical applications or research should follow the guidelines.86 MESs have the following characteristics: random occurrence during the cycle; brief duration (usually <0.1 second); high intensity (>3 dB over background); primarily unidirectional signals (if fast Fourier transformation is
used); and audible component (Fig. 17, Supplementary Videos 27, 28).

**VASOMOTOR REACTIVITY**

Vasomotor reactivity (VMR) reflects the ability of cerebral resistance arterioles to constrict and dilate to the stimuli (such as acetazolamide, 5% CO₂ inhalation, breath-holding, rebreathing in a closed mask or a semi-closed mask) and one of the cerebral autoregulation to maintain constant cerebral blood flow.⁸⁷⁻⁹¹ The breath holding test will be one of the commonly used stimuli for VMR (Fig. 18A, Supplementary Video 29).

VMR is reduced in steno-occlusive disease of ICA⁹² (Fig. 18B, Supplementary Video 30), advanced small

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![Fig. 17. Microembolic signals. (A-C) HITS at multiple vascular segments (right PCA, right siphon, and left ACA). (D) HITS at left ACA. TCD; transcranial Doppler, HITS; high intensity transient signals, ACA; anterior cerebral artery, PCA; posterior cerebral artery.](image)

![Fig. 18. Vasomotor reactivity (A) Monitoring of bilateral MCA during a 30-second breath holding test. (B) Decreased vasomotor reactivity during CO₂ inhalation. MCA; middle cerebral artery.](image)
artery disease, MCA stenosis, and sports-related concussion. While the reduced VMR correlates with severity of stenosis and may predict the risk of future stroke in patients with ICA stenosis or extracranial arterial occlusion, the significance of reduced VMR in patients with MCA and other large intracranial arterial stenosis is not well known yet.

SUPPLEMENTARY MATERIALS

Supplementary materials related to this article can be found online at https://doi.org/10.3172/jnn.2018.00039.

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