Validation of transcranial Doppler ultrasound with a stereotactic neurosurgical technique

Lee H. Monsein, M.P.H., M.D., Alex Y. Razumovsky, Ph.D., Stacey J. Ackerman, M.S.E., Haring J. W. Nauta, M.D., Ph.D., and Daniel F. Hanley, M.D.

Departments of Radiology and Radiological Science and of Neurology, Johns Hopkins University, Baltimore, Maryland; and Department of Neurosurgery, University of Texas, Galveston, Texas

Vessel identification during a transcranial Doppler (TCD) ultrasound examination is usually based on well-established inferential criteria without confirmation by imaging. Part of a routine study involves taking measurements from the M₁ segment of the middle cerebral artery (MCA) and the A₁ segment of the anterior cerebral artery (ACA) at the points of maximum mean linear blood flow velocity (LBFV). The authors tested the hypothesis that insonation is from the midpoints of the M₁ and A₁ segments during clinical TCD examinations.

Conventional hand-held TCD examinations were performed on five volunteers. The points of maximum mean LBFV of the M₁ and A₁ segments of the MCA and ACA were located. Measurements were also taken from the midpoints of the M₁ and A₁ segments using a magnetic resonance (MR) imaging–guided stereotactic TCD technique. Values for depths of insonation and maximum mean LBFV obtained with the two techniques were compared. There was no significant difference between the two techniques for the measured values of depth of insonation of either the individual vessels (p > 0.11) or the aggregate (p = 0.46). There was a significant difference between the aggregate maximum mean LBFV measurements (p = 0.0022). The hand-held technique systematically produced higher maximum mean LBFV than the MR-guided stereotactic technique. The authors conclude that when using traditional criteria for TCD examination of the ACA and MCA, the points of insonation approximate the middle of the A₁ and M₁ segments.

Key words • transcranial Doppler ultrasound • stereotactic imaging • middle cerebral artery • anterior cerebral artery

The Doppler theory was first formulated in 1842 by the Austrian physicist Christian Doppler and was verified by the Dutch physicist Buys Ballot 3 years later.¹ The application of the Doppler principle to the noninvasive study of the intracranial circulation was suggested by Kaneko² as early as 1960. It was not until 1981, however, that the first transcranial Doppler (TCD) ultrasound examination was performed by Aaslid, et al.³ Since that time, TCD has been used to study a variety of cerebrovascular diseases.

Transcranial Doppler ultrasound is especially useful in situations requiring serial examinations. This places great importance on the ability to obtain reproducible measurements from precise vascular locations. Inferential criteria have been described to facilitate this process,²,⁴,⁷ but because the vessel of interest is not directly visualized, routine TCD examinations without color Doppler remain essentially “blind.” Part of a clinical hand-held TCD examination involves taking measurements from the M₁ segment of the middle cerebral artery (MCA) and the A₁ segment of the anterior cerebral artery (ACA) at the points of maximum mean linear blood flow velocity (LBFV).

Magnetic resonance (MR) imaging–guided stereotactic techniques have recently been developed that allow precise in vivo anatomical localizations.¹⁰ Using such a system, we tested the hypothesis that during clinical TCD examination we are insonating from the midpoints of the M₁ and A₁ segments. We also compared our routine maximum mean LBFV measurements with those obtained using the MR-guided stereotactic technique.

Clinical Material and Methods

Transcranial Doppler studies were performed on five healthy volunteers with a mean age of 34.7 ± 6.7 years (± standard deviation) using a hand-held 2 MHz pulsed-wave Doppler probe.* All examinations were performed by the same skilled sonographer, who had 8 years of experience, using criteria for vessel identification that have been detailed previously.²,⁴,⁷ The M₁ segment of the MCA and the

* Transpsect Doppler probe obtained from Medasonics, Fremont, California.
A segment of the ACA were located bilaterally through the ipsilateral temporal window using a conventional hand-held technique. The point of maximum mean LBFV was found and recorded, as was the depth of insonation.

Each subject was fitted with a thermoplastic face mask. An MR-compatible Brown-Roberts-Wells (BRW) stereotactic head ring was affixed to the face mask by four graphite pins. The pins were numbered and marked to allow repeated fixation. An MR-compatible BRW localizer frame was then attached to the head ring (Fig. 1 left). A 1.5-tesla MR instrument was used to obtain contiguous 3 to 4-mm thick gradient echo images. The repetition time was 34 to 51 msec; echo time was 13 to 15 msec; there were 2 to 4 excitations; and the flip angle was 30°. The absence of geometric distortion due to a susceptibility artifact of the MR-guided stereotactic system was confirmed, as has been previously described.12 The three-dimensional coordinates of the midpoint of the M₁ and A₁ segments were determined using the standard software of the BRW system.

The localizer frame was removed from the head ring and replaced by a Cosman-Roberts-Wells arc frame. A specially fabricated probe adapter allowed the same Doppler probe used for the hand-held examinations to be used with the arc frame (Fig. 1 right).

The Doppler probe was positioned over the same point of the temporal window used for the hand-held technique. The midpoints of the M₁ and A₁ segments were identified by altering the depth and angle of insonation according to the three-dimensional coordinates identified with MR imaging. The calculated depth of insonation and measured maximum mean LBFV were recorded from this position. The calculated depth of insonation was determined by subtracting the distance from the probe holder to the skin from 16 cm, which is the fixed distance from the holder to the isocenter of the arc frame.

The mean and range of the depth of insonation and maximum mean LBFV measurements were tabulated by vessel and technique. The mean difference (X̄) between the MR-guided stereotactic and the hand-held measurements of depth of insonation and maximum mean LBFV from individual vessel and from the aggregate was calculated.

The two types of measurements obtained from individual vessels and from the aggregate using the two techniques were compared using the nonparametric Wilcoxon signed-rank test for paired data. Significance was inferred at p < 0.05.

Correlation coefficients (r) indicating the degree of association between MR-guided stereotactic and hand-held measurements were determined by simple linear regression for the aggregate data. Depth of insonation and maximum mean LBFV regression lines were plotted against the line of identity (45° line) to investigate the presence of a systematic bias between the techniques.

For the aggregate data, the detectable difference between depth of insonation measurements obtained with the two techniques was calculated using the sample size formula for two independent group means, adjusted for the degree of observed correlation (r) between the groups (power = 80%; α = 0.05, two sided). The standard deviation (σ) of the depth of insonation was calculated based on the weighted mean of the variances (weighted by individual vessel sample sizes).

Results

All 20 vessels sought were found with both techniques. The means and ranges of the depth of insonation and maximum mean LBFV data are listed in Table 1. The mean difference between the hand-held and MR-guided stereotactic maximum mean LBFV of individual vessels ranged from 4.2 to 7.4 cm/sec and the mean difference in depth of insonation ranged from −0.8 to 1.2 mm (Table 2).

There was no significant difference between the hand-held and MR-guided stereotactic depth of insonation measures for either the individual vessels or the aggregate. In contrast, aggregate data for maximum mean LBFV indicated that hand-held measurements were significantly
yet systematically (5.6 cm/sec) greater than MR-guided stereotactic measurements (p = 0.0022, Wilcoxon signed-rank test).

In the aggregate, the correlations were excellent among MR-guided stereotactic and hand-held measurements of depth of insonation and maximum mean LBFV (r = 0.96 and r = 0.88, respectively), as displayed in Fig. 2. Our aggregate data (20 vessels) demonstrated a power of 80% to detect a difference in depth of 0.75 mm between the hand-held and MR-guided stereotactic techniques (σ = 4.22 mm, r = 0.96).

Discussion

Since its introduction in 1982, there have been a number of technological enhancements in TCD, including microprocessor controls, analog–digital outputs, flow mapping, time sequencing of transducers, multichannel acquisitions, and superimposed static gray-scale and color Doppler sonography. Even so, the methods by which a vessel is identified using most clinical TCD instruments have not changed significantly.

To confidently identify a cerebral vessel with conventional TCD, one must know the cranial window used, the angle of insonation, the depth of the sample volume, the direction of flow in relation to the transducer, the spatial relationship of the vessel being investigated to the bifurcation of the internal carotid artery, and the response to common carotid artery compression and/or oscillation maneuvers. These criteria appear to be adequate for experienced operators, as evidenced by minimal intra- and interobserver variabilities. Anatomical studies in cadavers have been used to validate the TCD examination, but attempts to validate these criteria in vivo have been limited. Recently, direct imaging of the basilar vessels with transcranial color duplex sonography has become possible. Nevertheless, these investigations have not established that during a clinical TCD examination without color Doppler, it is the midpoints of the ACA and MCA that are being insonated.

In our study, the depths of insonation of the M1 segment of the MCA and the A1 segment of the ACA with the hand-held technique were similar to those previously reported. Because the temporal windows and depths of insonation for both the hand-held and MR-guided stereotactic techniques were almost identical, we were most likely insonating from the midpoint of the M1 and A1 segments with the hand-held technique.

The systematically greater maximum mean LBFV achieved with the hand-held technique can be explained by one of two factors: a difference in angle of insonation or “off-center” insonation with the MR-guided stereotactic technique. The maximum mean LBFV has been shown to be very sensitive to small changes in the angle of insonation. With the hand-held technique, this angle is easily changed to optimize maximum mean LBFV. With the MR-guided stereotactic technique, however, the angle of insonation can be varied only minimally, therefore hindering such optimization.

Using a methodology similar to that of Finn, et al., we calculated that the difference in the maximum mean LBFV between the hand-held and MR-guided stereotactic techniques could be accounted for by differences in the angles of insonation between the two techniques. For the left and right MCA these differences were approximately 21.2° (95% confidence interval, t-distribution 15.1° to 51.9°) and 28.7° (95% confidence interval, 19.5° to 65.6°), respectively. The difference may also be due to intraobserver variability.
Stereotactic vs. hand-held transcranial Doppler techniques

A difference in the values of maximum mean LBFV between the hand-held and MR-guided stereotactic technique that was due to differences in the angle of insonation would be expected to be random, and therefore would not produce the systematic difference we observed. Furthermore, the calculated differences in angle of insonation necessary to account for this systematic difference were not observed. In contrast, a difference due to “off-center” insonation of the vessel of interest, due to minimal inaccuracies of the rigid frame, would be expected to produce such a systematic difference.

The MR-guided stereotactic technique is too cumbersome and not necessary for routine clinical TCD studies. However, we found it useful for the in vivo validation of hand-held TCD examinations. We have used it in defining the origin of Doppler signals that occur at an unexpected depth of insonation. For example, during insonation of one of our volunteers via the suboccipital approach, Doppler signals were detected at a depth of insonation of 11 cm. Using the MR-guided stereotactic technique, we determined that the origin of these signals was the M1 segment of the MCA. We also believe the MR-guided stereotactic technique may be of potential research value in the serial study of the maximum mean LBFV of abnormal vessels detected on MR imaging until direct velocity measurements on MR imaging are possible.

In conclusion, this study confirmed that when using traditional hand-held TCD criteria, the midpoints of the M1 segment of the MCA and the A1 segment of the ACA are reliably located.

Acknowledgments

The authors would like to thank Mark S. Schnitzer, Scott W. Wells, Andrew Belkin, and Deborah Mandelblatt for volunteering as TCD subjects; Cheryl L. Moser for performing the MR studies; R. Nick Bryan and Jonathan H. Gillard for reviewing the manuscript; and Howard A. Conner for fabricating the TCD probe adapter.

References


Address reprint requests to: Lee H. Monsein, M.D., Department of Radiology, Johns Hopkins Hospital, 600 N. Wolfe Street, Houck B112C, Baltimore, Maryland 21287–2182.
<table>
<thead>
<tr>
<th>Vessel</th>
<th>No. of Pairs</th>
<th>HH DOI (mm)</th>
<th>MRGS DOI (mm)</th>
<th>HH MMLBFV (cm/sec)</th>
<th>MRGS MMLBFV (cm/sec)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Mean</td>
<td>Range</td>
<td>Mean</td>
<td>Range</td>
</tr>
<tr>
<td>lt MCA</td>
<td>5</td>
<td>49.8</td>
<td>48–51</td>
<td>49.8</td>
<td>47–57</td>
</tr>
<tr>
<td>lt ACA</td>
<td>5</td>
<td>63.8</td>
<td>54–74</td>
<td>64.6</td>
<td>53–74</td>
</tr>
<tr>
<td>rt MCA</td>
<td>5</td>
<td>50.6</td>
<td>50–51</td>
<td>49.4</td>
<td>48–51</td>
</tr>
<tr>
<td>rt ACA</td>
<td>5</td>
<td>63.4</td>
<td>59–65</td>
<td>62.8</td>
<td>60–65</td>
</tr>
</tbody>
</table>

*HH = hand-held; DOI = depth of insonation; MRGS = magnetic resonance imaging-guided stereotactic technique; MMLBFV = maximum mean linear blood flow velocity; MCA = middle cerebral artery; ACA = anterior cerebral artery.
**TABLE 2**

Mean difference between HH and MRGS transcranial Doppler measurements of MMLBFV and DOI*

<table>
<thead>
<tr>
<th>Vessel</th>
<th>No. of Pairs</th>
<th>DOI (mm)</th>
<th></th>
<th>MMLBFV (cm/sec)</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>$X_d$</td>
<td></td>
<td>$p$</td>
<td>$X_d$</td>
</tr>
<tr>
<td>lt MCA</td>
<td>5</td>
<td>0</td>
<td></td>
<td>1.0</td>
<td>4.2</td>
</tr>
<tr>
<td>lt ACA</td>
<td>5</td>
<td>-.8</td>
<td></td>
<td>.46</td>
<td>4.2</td>
</tr>
<tr>
<td>rt MCA</td>
<td>5</td>
<td>1.2</td>
<td></td>
<td>.11</td>
<td>7.4</td>
</tr>
<tr>
<td>rt ACA</td>
<td>5</td>
<td>.6</td>
<td></td>
<td>.70</td>
<td>6.6</td>
</tr>
<tr>
<td>aggregate</td>
<td>20</td>
<td>.25</td>
<td></td>
<td>.46</td>
<td>5.6</td>
</tr>
</tbody>
</table>

* HH = hand-held; MRGS = magnetic resonance imaging-guided stereotactic technique; DOI = depth of insonation; MMLBFV = maximum mean linear blood flow velocity; $X_d$ = mean difference (HH minus MRGS technique); p = p-value Wilcoxon signed-rank test; MCA = middle cerebral artery; ACA = anterior cerebral artery.