Power M-Mode Doppler and Single-Gate Spectral Analysis
Using a 2-MHz Pulsed-Wave Doppler Transducer to
Directly Detect Cervical Internal Carotid Artery Stenosis

Use of the Continuity Principle: Report of a Novel Technique

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Background and Purpose—We hypothesized that direct cervical investigation with Power M-Mode Doppler (PMD) combined with single-gate Doppler spectral analysis (SGDSA) using a 2-MHz pulsed-wave Doppler transducer would show reasonable accuracy parameters when compared with standard color-coded carotid duplex ultrasound (CDU).

Methods—We prospectively screened for cervical internal carotid artery (ICA) stenosis by direct observation using a 2 MHz PMD/SGDSA device. PMD identified the artery (location, depth, flow direction) and SGDSA assessed waveform; peak systolic, end diastolic, and mean flow velocities (MFV) of the common carotid artery; cervical ICA proximally and distally; and external carotid artery. Diagnostic accuracy was compared with concurrent carotid duplex ultrasound. The continuity principle was applied using the proximal/distal cervical ICA MFV ratio.

Results—We examined 456 vessels (228 patients). Using ICA proximally/ICA distally MFV ratio of 1.5 or greater or absence of ICA signature, for 40% to 59% or greater stenosis (including occlusions), sensitivity was 75.4%, specificity 99.8%, positive predictive value 97.7%, negative predictive value 96.6%, and accuracy 96.7%. For MFV ratio 1.6 or greater or absence of ICA signature and 60% to 79% or greater stenosis (including occlusions), sensitivity was 92.3%, specificity 98.1%, positive predictive value 81.8%, negative predictive value 99.3%, and accuracy 97.6%.

Conclusions—Use of combined PMD and SGDSA to directly observe the extracranial ICA is reasonably accurate compared with carotid duplex ultrasound. Using the MFV ratio of proximal/distal extracranial ICA improves accuracy parameters and provides a quick and effective bedside screen for ICA stenosis. This novel technique should be considered part of the standard PMD/transcranial Doppler examination. (Stroke. 2007;38:1780-1785.)

Key Words: carotid artery disease ■ Power M-Mode Doppler ■ transcranial Doppler ■ ultrasonics/ultrasound

For stroke prevention,1,2 the identification of carotid plaques and quantification of stenosis is of primary importance. Reliable noninvasive tests are needed to detect internal carotid artery (ICA) disease in high-risk patients.3–5 Rapid diagnosis of significant carotid stenosis and occlusion is important for the management of patients, especially in the setting of acute stroke. Transcranial Doppler (TCD) is noninvasive, inexpensive, convenient, portable, and can quickly provide a global image of the hemodynamic status of cerebral circulation in patients with stroke as a complementary test to refine other imaging findings and detect tandem lesions. Numerous studies have shown that TCD can assess downstream effects of proximal ICA obstruction and intracranial ICA flow.6–8 Transcranial Power M-Mode Doppler (PMD)9 uses a 2-MHz digital Doppler having 33 overlapping Doppler sample gates placed with 2-mm spacing configured to simultaneously display the intensity and direction of the blood flow signatures over 6 cm of depth. The brighter PMD colors reflect stronger intensities; this “road map” can serve as a guide for spectral analysis.

We combined PMD and single-gate Doppler spectral analysis (SGDSA) using a 2-MHz pulsed-wave Doppler transducer directly over the cervical ICA in a novel technique to detect hemodynamically significant stenosis. We hypothesized that this technique would show reasonable accuracy parameters for 40% to 59% or greater and 60% to 79% or greater stenosis compared with standard color-coded carotid duplex ultrasound (CDU) when applying the principle of continuity of flow in the unbranching ICA.10

Subjects and Methods
Both inpatients and outpatients referred to our neurosonology laboratory for symptoms of cerebrovascular disease were prospectively screened for cervical ICA stenosis by direct cervical artery observa-
tion using a portable digital 2-MHz PMD/spectral TCD unit (TCD 100 M; Spencer Technologies, Seattle, Wash.). The intracranial arteries were examined through conventional temporal, foraminal, and orbital windows.\textsuperscript{11} We then examined the cervical carotid arteries according to a protocol technically similar to a continuous-wave Doppler carotid examination. PMD was used as a guide to identify the artery (location, depth, flow direction, and signature as to low or high-resistance type) and SGDSA assessed waveform; peak systolic (PSV), end diastolic (EDV), and mean flow velocities (MFV); and pulsatility index of common carotid artery (CCA), proximal ICA, distal cervical ICA, and external carotid artery (ECA). With experience, a unilateral cervical carotid system can be examined in less than 4 minutes. The cervical PMD/SGDSA insonation protocol we used is provided in the Appendix.

Separate local Intersocietal Commission for the Accreditation of Vascular Laboratories (ICAVL)-certified ultrasound laboratories performed the CDU studies using a standard insonation protocol and diagnostic criteria\textsuperscript{3,4} by means of an ATL 5000 ultrasound system with a linear 7- to 4-MHz probe. The results were expressed as a percent stenosis range: 0%, 1% to 39%, 40% to 59%, 60% to 79%, 80% to 99% stenosis, and occlusion. Both the CDU and PMD/TCD examiners, highly experienced and American Registry for Diagnostic Medical Sonography (ARDMS)-registered, were each blind to the other neurodiagnostic imaging results.

Patients with concurrent CDU performed within 90 days of PMD/TCD, as the gold standard, were compared for diagnostic accuracy of 40% to 59% or greater and 60% to 79% or greater stenosis (including occlusions).

We calculated the ICA/CCA systolic and diastolic ratios, and, according to the principle of continuity of flow (a principle of mass conservation for a steady, one-dimensional flow, with one inlet and one outlet, which expresses the connection between mean flow velocity and cross-sectional area) in the unbranching ICA,\textsuperscript{10} the proximal/distal ICA MFV ratios, and compared them with the CDU findings. Receiver operating characteristics curves were generated to predict a 40% to 59% or greater stenosis (including occlusion), and 60% to 79% or greater stenosis (including occlusion). These curves describe the variation of the sensitivity, specificity, positive predictive value (PPV), negative predictive value (NPV), and overall accuracy for different values of the velocity ratios used as a cutoff to detect stenosis. They permit one to choose the best cutoff, ie, the one that produces the highest accuracy possible.

**Results**

We examined 228 patients (456 unilateral cervical vessel examinations) who had symptoms of cerebrovascular disease and complete PMD examinations and duplex scanning data. The time interval between PMD/TCD and CDU was limited to 90 days (average, 12 days; median, 2 days).

Mean patient age was 68.9 years (SD = 11.6; range, 32 to 95 years); 50.9% were males. Of the 456 cervical ICAs, CDU diagnosed 57 (12.5%) stenoses of 40% to 59% or greater, including occlusions. Of these 57 stenoses, 39 (68.4%) were equal or greater than 60% to 79%, including occlusions. Nine occlusions were diagnosed by CDU, representing 2% of the entire carotid sample.

Figures 1 and 2 show sensitivity, specificity, PPV, NPV, and accuracy for various values of velocity ratios used as a cutoff to predict 40% to 59% or greater stenosis and 60% to 79% or greater stenosis and occlusion. We referred to stenosis range instead of a certain stenosis value (eg, 40% to 59% instead of 50%) because CDU results were given in these stenosis percent ranges.

Using the continuity principle, ie, the proximal/distal ICA MFV ratios in predicting a 40% to 59% or greater stenosis and occlusion (Figure 1), an ICA MFV ratio of 1.5 rendered an accuracy of 96.7% (95% CI: 95.1% to 98.3%). Sensitivity
was 75.4% (95% CI: 71.4% to 79.4%), specificity 99.8% (95% CI: 99.4% to 100%), PPV 97.7% (95% CI: 96.3% to 99.1%), and NPV 96.6% (95% CI: 94.9% to 98.3%). For a 60% to 79% or greater stenosis or occlusion, at a cutoff ICA MFV ratio of 1.6 (Figure 2), sensitivity was 92.3% (95% CI: 89.9% to 94.7%), specificity 98.1% (95% CI: 96.8% to 99.4%), PPV 81.8% (95% CI: 78.3% to 85.3%), NPV 99.3% (95% CI: 98.5% to 100%), and accuracy 97.6% (95% CI: 96.2% to 99.0%).

Using ICA/CCA PSV ratios and EDV ratios, the accuracy parameters obtained for the best cutoff ratios to predict 40% to 59% or greater and 60% to 79% or greater ICA stenosis or occlusion were somewhat lower than those found using the continuity principle.

Tables 1 and 2 summarize the accuracy parameters of the 3 methods used for predicting a 40% to 59% or greater (Table 1) and a 60% to 79% or greater (Table 2) ICA stenosis or occlusion.

**Discussion**

Numerous studies have shown that TCD ultrasound can indirectly detect extracranial ICA significant stenosis and occlusion through assessment of intracranial flow changes. Based on various gold standards such as cerebral angiography, digital subtraction angiography or MR angiography, digital subtraction angiography, MR angiography, or CDU, or even en bloc endarterectomy specimens, prevalence and/or accuracy parameters of certain intracranial flow findings in ICA severe obstruction were reported. In one study of 517 patients with concurrent angiography or CDU as the gold standard, Christou et al reported the following accuracy parameters for a 70% to 99% extracranial carotid stenosis or occlusion: sensitivity 79%, specificity 86%, PPV 54%, NPV 95%, and accuracy 84%.

Our study intends to show that TCD can not only detect intracranial flow changes in a severe extracranial ICA stenosis or occlusion, but it can also approach directly the cervical carotid arteries in an attempt to improve diagnostic accuracy of this method for significant ICA obstruction when a PMD-guided single-gate spectral analysis device, using a 2-MHz pulsed wave transducer, is used alone. This is especially useful in patients with either suboptimal transcranial windows, in which intracranial blood flow changes are hardly recognizable attributable to skull characteristics or lower grades of extracranial ICA stenosis in which collateral flow patterns have not yet developed or are atypical. However, extracranial PMD/SGDSA is not the preferred technique to be combined with PMD/TCD to detect extracranial

**TABLE 1. Summary of Accuracy Parameters of 3 Methods Used to Predict a 40% to 59% or Greater ICA Stenosis or Occlusion**

<table>
<thead>
<tr>
<th>Criteria</th>
<th>MFV Ratio Method</th>
<th>PSV Ratio Method</th>
<th>EDV Ratio Method</th>
</tr>
</thead>
<tbody>
<tr>
<td>Best cutoff ratio</td>
<td>1.5</td>
<td>1.5</td>
<td>2.6</td>
</tr>
<tr>
<td>Sensitivity</td>
<td>75.4%</td>
<td>73.7%</td>
<td>64.9%</td>
</tr>
<tr>
<td>95% CI</td>
<td>71.4% to 79.4%</td>
<td>69.7% to 77.7%</td>
<td>60.5% to 69.3%</td>
</tr>
<tr>
<td>Specificity</td>
<td>99.8%</td>
<td>97.5%</td>
<td>99.0%</td>
</tr>
<tr>
<td>95% CI</td>
<td>99.4% to 100%</td>
<td>96.1% to 98.9%</td>
<td>98.1% to 99.9%</td>
</tr>
<tr>
<td>PPV</td>
<td>97.7%</td>
<td>80.8%</td>
<td>90.2%</td>
</tr>
<tr>
<td>95% CI</td>
<td>96.3% to 99.1%</td>
<td>77.2% to 84.4%</td>
<td>87.5% to 92.9%</td>
</tr>
<tr>
<td>NPV</td>
<td>96.6%</td>
<td>96.3%</td>
<td>95.2%</td>
</tr>
<tr>
<td>95% CI</td>
<td>94.9% to 98.3%</td>
<td>94.6% to 98.0%</td>
<td>93.2% to 97.2%</td>
</tr>
<tr>
<td>Accuracy</td>
<td>96.7%</td>
<td>94.5%</td>
<td>94.7%</td>
</tr>
<tr>
<td>95% CI</td>
<td>95.1% to 98.3%</td>
<td>92.4% to 96.6%</td>
<td>92.6% to 96.8%</td>
</tr>
</tbody>
</table>

**TABLE 2. Summary of Accuracy Parameters of 3 Methods Used to Predict a 60% to 79% or Greater ICA Stenosis or Occlusion**

<table>
<thead>
<tr>
<th>Criteria</th>
<th>MFV Ratio Method</th>
<th>PSV Ratio Method</th>
<th>EDV Ratio Method</th>
</tr>
</thead>
<tbody>
<tr>
<td>Best cutoff ratio</td>
<td>1.6</td>
<td>2.2</td>
<td>3.1</td>
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<tr>
<td>Sensitivity</td>
<td>92.3%</td>
<td>66.7%</td>
<td>73.7%</td>
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<tr>
<td>95% CI</td>
<td>89.9% to 94.7%</td>
<td>62.4% to 71.0%</td>
<td>69.7% to 77.7%</td>
</tr>
<tr>
<td>Specificity</td>
<td>98.1%</td>
<td>99.5%</td>
<td>99.5%</td>
</tr>
<tr>
<td>95% CI</td>
<td>96.8% to 99.4%</td>
<td>98.9% to 100%</td>
<td>98.9% to 100%</td>
</tr>
<tr>
<td>PPV</td>
<td>81.8%</td>
<td>92.9%</td>
<td>93.3%</td>
</tr>
<tr>
<td>95% CI</td>
<td>78.3% to 85.3%</td>
<td>90.5% to 95.3%</td>
<td>91.0% to 95.6%</td>
</tr>
<tr>
<td>NPV</td>
<td>99.3%</td>
<td>97.0%</td>
<td>97.7%</td>
</tr>
<tr>
<td>95% CI</td>
<td>98.5% to 100%</td>
<td>95.4% to 98.6%</td>
<td>96.3% to 99.1%</td>
</tr>
<tr>
<td>Accuracy</td>
<td>97.6%</td>
<td>96.7%</td>
<td>97.4%</td>
</tr>
<tr>
<td>95% CI</td>
<td>96.2% to 99.0%</td>
<td>95.1% to 98.3%</td>
<td>95.9% to 98.9%</td>
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carotid stenosis and cannot replace CDU. CDU alone (or preferably in combination with TCD) is fully sufficient to diagnose extracranial carotid stenosis; it can precisely evaluate the characteristics of plaque as well as the degree of stenosis. PMD/TCD and extracranial PMD/SGDSA may be an alternative to CDU in case CDU is not available or in case of a need for a screening or quick bedside examination in the setting of acute cerebrovascular accident.

Because angle correction is not available with cervical PMD/spectral Doppler velocity measurements, grading carotid stenosis is not accurate based on single velocity cutoff values. Instead, velocity ratios can normalize for various situations such as patient variation, interobserver and interequipment variability, or conditions such as contralateral ICA severe obstruction, tandem stenosis, cardiac failure, hyperemic flow, and so on. Of our 3 methods, the best predictor for both a 40% to 59% or greater ICA stenosis or occlusion (Table 1) and a 60% to 79% or greater ICA stenosis or occlusion (Table 2) was the MFV ratio of proximal/distal extracranial ICA as expected from applying the principle of continuity of flow in the unbranching ICA.5,10 Ranke et al11 analyzed various Doppler parameters in 44 patients undergoing carotid angiography and showed that ICA intrastenotic to distal mean velocity ratio measurement is superior to ICA/CCA velocity ratios or absolute flow velocity measurements with angle-corrected CDU for 2 reasons: 1) because of its extracranial course without branches, the ICA meets the requirements of the continuity equation; and 2) velocity for ICA-based ratios is measured proximally and distally corresponding to angiographic diameter ratio measurements with NASCET criteria.1 For similar degrees of ICA stenosis, as diagnosed by our “gold standard,” ie, CDU, we obtained much lower cutoff values of the MFV ratio: 1.5 and 1.6, respectively.

In our measurements with the PMD/SGDSA device, the velocities are displayed assuming a Doppler angle of zero degrees, which actually is not the case. Especially for the proximal ICA, the measured velocities are much lower than the angle-corrected velocities from CDU, reducing the numerator considerably. On the other hand, the denominator of the ratio, the distal ICA velocity measurement, may be similar or even larger with PMD/SGDSA compared with CDU measurements for 2 reasons: 1) the insonation angle does not need to be corrected when approaching the ICA with the PMD/SGDSA probe several centimeters distal to the angle of the mandible at its farthest cervical segment where the Doppler angle is not significantly different from zero degrees; and 2) at that site of PMD/SGDSA velocity measurement, the effect of poststenotic dilatation, turbulences, and subsequent velocity decrease might not be as evident as it is at the site of CDU accessibility for what is called “distal” ICA when performing CDU with a considerably large linear or phased-array transducer.

A significant limitation of our study is the use of CDU, instead of angiographic methods, as our gold standard for grading ICA stenosis. Few angiograms are being performed in routine practice, and in the present study, the number of MR angiographies or digital subtraction angiographies performed is less than acceptable for any correlation purposes; however, future correlation with angiography would be ideal.

Another major weakness of the present study is that no comparison has been made with continuous-wave Doppler, which is very commonly used, either alone or in combination with CDU, as the standard examination tool for the cervical arteries in many European countries. Recently, Schminke et al15 compared continuous-wave Doppler, as a potential screening examination, with CDU, as the standard ultrasound examination technique. Their study protocol was rather similar to ours, except for investigating a smaller number of patients. In their study, all stenoses greater than 75% and occlusions were classified correctly with continuous-wave Doppler, whereas the accuracy for stenoses greater than 50% was 78%.

Despite limitations, the combined use of PMD and SGDSA to directly observe the extracranial ICA is reasonably accurate for 40% to 59% or greater and 60% to 79% or greater stenosis or occlusion compared with CDU. The use of the MFV ratio of proximal/distal extracranial ICA improves accuracy parameters and makes this a quick and effective bedside screen for ICA stenosis, especially in the setting of acute cerebrovascular accident. In addition, because the examination of a unilateral cervical carotid system takes 4 minutes or less, this novel technique should be considered part of the standard PMD/TCD examination but should not be considered a standalone diagnostic test. Thus, in extracranial ICA severe obstruction, the overall yield of a PMD/TCD examination that includes a direct carotid screening could be higher than that of a TCD test that relies only on the indirect findings of certain intracranial flow alterations.

Appendix
Our cervical PMD/SGDSA insonation protocol starts with the examination of the CCA low in the neck (Figure 3A).

The patient is supine with the head slightly rotated to the opposite direction. The PMD display depth is set at 30 to 80 mm. For CCA, ECA, and proximal ICA assessment, the power output can be set at 10% in most normal cases, whereas for distal ICA, it is set at 100%. The noise levels are set to allow minimal background signal on PMD display. The transducer is applied to the anterolateral aspect of the patient’s neck at a level placed below the presumed site of the carotid bifurcation (the superior margin of the thyroid cartilage) with the active surface of the transducer pointing inferiorly toward the sternocleidomastoid joint. A large amount of contact gel is needed to ensure transmission of the ultrasound beam into tissues. If no signals appear, the transducer is moved slowly laterally or medially without changing its angle with the skin surface until the CCA approaching (color-coded in red) flow signature appears on the PMD display and the intermediate resistance type of CCA spectrogram is obtained. In general, attempts should be made to find a window with maximum spatial presence of the carotid arteries flow signature. In other words, the PMD screen should be filled with color signals over a maximum depth range for the Doppler angle to be lowered as much as possible. Waveform assessment and velocity measurements are then performed at the maximum depth possible and the highest velocity spectra are recorded. Alternatively, CCA insonation can be performed with the probe placed at the base of the neck, just above the clavicle, with its aperture pointing cephalad when a receding flow (color-coded in blue) is expected.

To insonate the proximal ICA, the transducer is placed over the anterior triangle of the neck just above the sterno-clavicular joint pointing superiorly toward the presumed site of the carotid bifurcation. While advancing the transducer cephalad, the intermediate
resistance type of CCA flow signature changes into the low-resistance and lower velocity flow signature of the carotid bulb at the level of the bifurcation. Sometimes spectral and audio disturbances are encountered here even in normal cases. Advancing the probe more distally and usually slightly laterally, the proximal ICA waveform is assessed and the highest velocities are measured (Figure 3B).

After returning to the carotid bifurcation, the ECA is insonated by advancing the probe superiorly and usually pointing it slightly medially (Figure 4A). Both the PMD and the spectral displays show a high-resistance ECA flow signature, and, in our experience, the superficial temporal artery tapping maneuver has proved to be a valuable differential diagnosis means in cases of ECA internalization.
The distal cervical ICA is assessed by advancing the transducer to the angle of the mandible (Figure 4B) and recording the highest velocities at the maximum depth displayed on the PMD window. Doppler signals should be optimized to avoid aliasing and to trace PSV and EDV components with envelope application. In case of atrial fibrillation, a single cardiac cycle with the highest velocities should be used for measurement, and manual cursor measurements should be applied when necessary.

Disclosures
Dr Merrill Spencer was the owner of the company that produces the PMD/TCD machines involved in the study. Dr Spencer has passed away since the article was written.

References
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Stroke. 2007;38:1780-1785; originally published online April 26, 2007;
doi: 10.1161/STROKEAHA.106.480491
Stroke is published by the American Heart Association, 7272 Greenville Avenue, Dallas, TX 75231
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Print ISSN: 0039-2499. Online ISSN: 1524-4628

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