The Journal for Vascular Ultrasound 36(3):199–204, 2012

Three-Dimensional Reconstruction of the Vessel Lumen as an Adjunct to the Cerebrovascular Duplex Evaluation

Francis J. Porreca, MD, FACS, RPVI;[1] Angela Rodriguez-Wong, MD, RVT, RPVI;[2] Joseph P. Hughes, RVT, RVS[2], FSVU

ABSTRACT ***Introduction.***—**Color-flow duplex ultrasound is effective in the detection and quantification of carotid artery disease; however, diameter reduction estimates are most commonly derived by Doppler velocity measurements. In addition, direct visualization of the vessel lumen is only possible through the use of more expensive potentially invasive imaging procedures, such as computed tomography angiography, magnetic resonance angiography, and conventional angiography. Described here is a method to determine vessel diameter of the internal carotid artery (ICA) by the use of three-dimensional (3D) reconstruction of b-mode data to generate luminal diameter estimates.**

Materials and Methods.—**A prospective review of 40 consecutive cerebrovascular duplex studies was performed. Testing protocols required transverse sweeps of the common carotid artery (CCA) and ICA in b-mode. Motion files were analyzed using software, which segmented the vessel lumen as the area of interest. The software created a 3D rendering of the lumen of the CCA and ICA. Vessel diameter reduction estimated by Doppler-derived velocities was then compared with the 3D rendering of the vessel lumen diameters.**

Results.—**There was a 99% ($n = 79$, $\rho = < 0.001$) correlation between velocity estimates and 3D visualization for estimating diameter reduction. Correlation for cases with less than 50% diameter reduction by duplex was 100% ($n = 66$, $\rho = < 0.004$), whereas correlation for cases with 50% or greater diameter reduction by duplex was 92% ($n = 13$, $\rho = < 0.03$).**

Conclusion.— **3D reconstruction of the vessel lumen shows a statistically significant correlation with velocity-derived diameter reduction measurements. Although more investigation with a larger group of patients is necessary, 3D reconstruction may be a valuable adjunct and may enhance the diagnostic capabilities of color-flow duplex ultrasound.**

Introduction

Color-flow duplex ultrasound (CFDU) is effective in the detection and quantification of carotid artery disease[1] and is traditionally the first diagnostic test performed when cerebrovascular disease is suspected. Doppler-derived velocity measurements using CFDU estimates diameter reduction on the basis that the greater the velocity, the narrower the lumen. Attempts to estimate diameter reduction directly from b-mode images have had mixed results.[2] Advanced imaging modalities, such as arteriography, computed tomography angiography (CTA), and magnetic resonance angiography (MRA), which directly estimate the vessel lumen diameter, have associated morbidity and mortality.[3] The consensus of a panel of experts in the field of vascular ultrasonography advised reporting internal carotid artery (ICA) stenosis as specific ranges.[4] The group of patients with 50–69% asymptomatic luminal stenosis may present management issues. According to the Asymptomatic Carotid Atherosclerosis Study,[5] asymptomatic patients with 60% stenosis may benefit from carotid endarterectomy, whereas those with <60% may not benefit. Accordingly, an accurate noninvasive method to determine precise luminal reduction would be valuable. Although each method of determining luminal reduction has drawbacks, the determination of direct vessel lumen diameter may enhance the diagnostic capabilities of all examinations. Described here is a method to determine residual lumen diameter in the ICA on the basis of three-dimensional (3D) reconstructions directly from b-mode ultrasound images generated during the CFDU examination.

From the [1]Montefiore Medical Center, University Hospital of the Albert Einstein College of Medicine, Bronx, New York; and [2]Navix Diagnostix, Inc., Taunton, Massachusetts.

Presented at the Society for Vascular Ultrasound Annual Conference in Chicago, Illinois, June 2011.

Address correspondence to: Francis J. Porreca, MD, FACS, RPVI, Montefiore Medical Center, University Hospital of the Albert Einstein College of Medicine, 3219 E. Tremont Avenue, Bronx, NY 10461. E-mail: fporreca@montefiore.org

Materials and Methods

The CFDU testing results of 40 consecutive patients with carotid bifurcation atherosclerosis were retrospectively reviewed. All patients gave consent under institutional review board monitoring. All studies were performed by one of two registered vascular technologists (RVTs), credentialed through the American Registry of Diagnostic Medical Sonographers (ARDMS; Bethesda, MD) or by a MD with the RVT and ARDMS Registered Physician in Vascular Interpretation (RPVI) credential. All studies were performed on a MyLab 70 CFDU unit (Biosound Esoate, Inc., Indianapolis, IN) using a mid-frequency linear array transducer (LA522e).

A standard cerebrovascular duplex evaluation (Table 1) was performed in addition to the institutional review board–approved study protocol. The study protocol was performed immediately after the standard evaluation and required additional two-dimensional (2D) b-mode transverse continuous sweeps from the proximal common carotid artery (CCA) through the distal cervical ICA in two planes—one anterior and one lateral. Images and motion files of the transverse sweeps were saved in "Digital Imaging and Communications in Medicine" (i.e. DICOM) compressed and uncompressed formats. All imaging files were anonymized and saved for postprocessing. A vascular surgeon with the RPVI credential interpreted the standard testing evaluations by using internally validated Doppler diagnostic criteria (Table 2) to estimate diameter reduction in the ICA. A <50% stenosis was not considered hemodynamically significant, whereas diameter reductions ≥50% were grouped as noted in Table 2.

The study motion files were evaluated by the use of 3D reconstruction software (*Visualize: Vascular*™, Medipattern, Toronto, Canada), which was used by the technologist to segment the lumen as the region of interest with the interpreting physician blinded to the CFDU results. The software created a 3D rendering of the lumen. The narrowest and the widest luminal diameters for each ICA were determined. Figure 1 shows a reconstruction of the entire length of one carotid artery segment with different angles and views.

Using the reconstruction software, we determined the maximum and minimum diameter points of the ICA residual lumen. The narrowest ICA diameter was compared with the normal diameter of the distal cervical ICA to determine the diameter reduction of the proximal ICA by use of the formula as shown in Figure 2.

Reconstruction diameter estimates (RDEs) were then compared with the Doppler diameter estimates (DDEs) obtained during the CFDU examination for each case. Statistical analysis was performed for all variables using SPSS (IBM statistical software product) methods, version 11. A ρ value < 0.05 was considered to be statistically significant. Average time to perform the study protocol bilaterally was 10 minutes.

Table 1

Standard Cerebrovascular Testing Protocol

Patient history and physical examination
- Evaluation of symptoms
- Documentation of risk factors
- Bilateral brachial blood pressures
- Pulse assessment and auscultation

B-mode imaging with and without color-flow Doppler
- Proximal CCA
- Mid CCA
- Distal CCA
- External carotid artery
- Proximal cervical ICA
- Mid cervical ICA
- Distal cervical ICA
- Proximal subclavian artery

Doppler evaluation, maintaining an angle of insonation of 60° or less
- Proximal, mid, and distal CCA
- Proximal external carotid artery
- Proximal, mid and distal ICA
- Vertebral artery between the vertebral bodies
- Proximal subclavian artery

Table 2

Internally Validated Doppler Velocity Criteria to Determine Diameter Reduction of the Proximal ICA

Diameter Reduction, %	Peak Systolic Velocity, cm/sec	End-Diastolic Velocity, cm/sec
0–49	<180	<80
50–69	>180	>80
70–79	>325	>100
80–99	>400	>125
100	0	0

The category 0–49% incorporates vessels without or with plaque detected during the b-mode imaging portion of the CFDU that do not have hemodynamically significant velocity changes.

Results

From March to November 2010, 40 consecutive patient examinations (male n = 21, female n = 19, age 29–92 years, average 71) were performed and the data reviewed. One side of one patient's evaluation was corrupted, leaving 79 sides available for analysis.

The study database is shown in Table 3. The results are shown in Table 4. Overall, there was 99% (ρ = 0.001, n = 79) correlation between RDE and DDE. In ICA lesions with less than 50% diameter reduction, there was 100% (ρ = 0.004, n = 66) correlation between RDE and DDE. In ICA lesions ≥ 50% reduction, there was a 92% (ρ = 0.03, n = 13) correlation between RDE and DDE.

Discussion

Duplex evaluation of the cervical cerebrovascular circulation has been used for several decades to noninvasively determine the location and severity of carotid artery disease.[6] B-mode imaging is used to determine

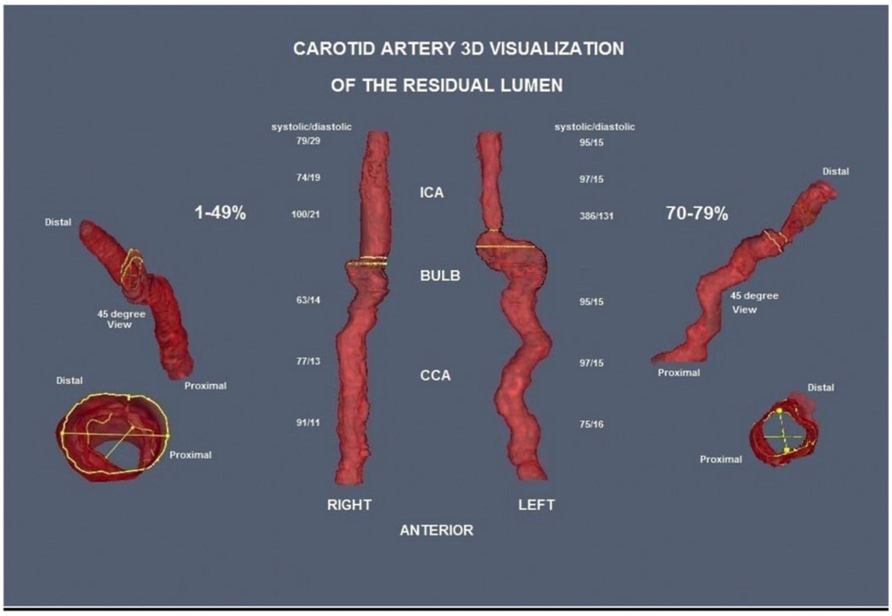

Figure 1

Visualization of carotid artery.

the location and extent of the disease process, whereas Doppler-derived velocities are used to estimate the diameter reduction of the vessel. The advantage of carotid duplex is that the anatomic B-mode image of the plaque can be combined with hemodynamic information derived by Doppler.

Controversy exists today as to what the gold standard is for the diagnosis of carotid artery stenosis. Previously, angiography was considered the optimum study. More recently MRA and CTA have been used to avoid the complications of contrast angiography. Still, others believe that CFDU is the gold standard diagnostic test. Each of these imaging modalities has its limitations. Contrast angiography is invasive, with potential risks of stroke and arterial injury occurring in the patient. The contrast can be toxic and can cause allergic reactions. MRA and CTA also involve the use of contrast agents. MRA tends to overestimate the degree of stenosis whereas CTA requires high radiation doses.[7] Finally, standard angiography, CTA, and MRA do not provide hemodynamic information. These studies are also more expensive than conventional CFDU. Expert

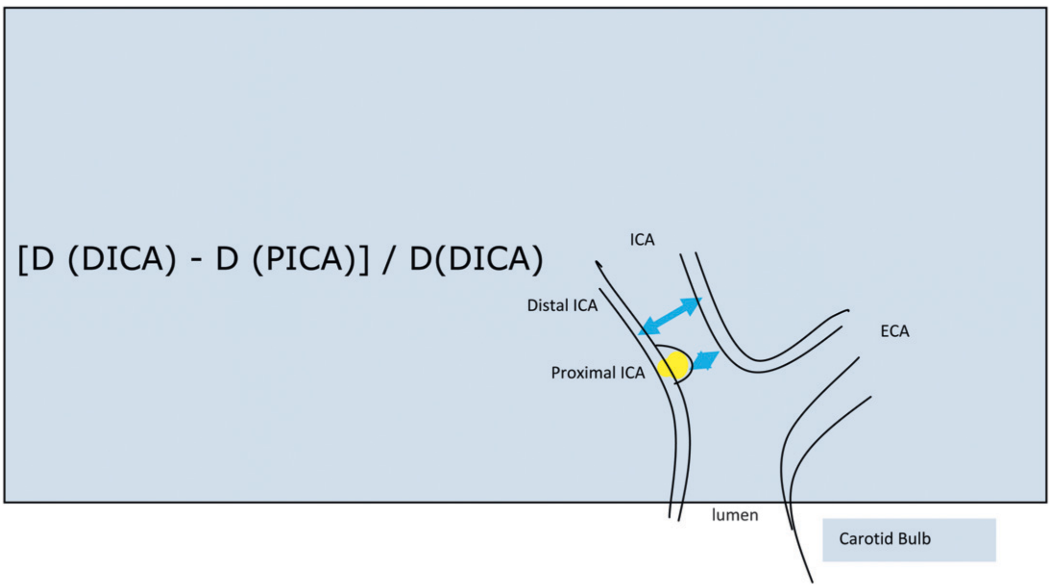

Figure 2

Luminal reduction calculation.

Table 3

Study Content

Stenosis Category	No. in the Study
0–49%	66
50–69%	8
70–79%	2
80–99%	2
100%	1
Total	79

consensus requires that the degree of stenosis be reported as a range.[4] In asymptomatic patients with 50–69% stenosis, this presents a dilemma. Depending on individual circumstances if the stenosis is closer to 50% one would be less likely to intervene whereas a stenosis closer to 70% would be an indication for intervention, as shown by the Asymptomatic Carotid Atherosclerosis Study. Patients with greater degrees of stenosis are more likely to have cerebrovascular symptoms. Clearly, it would be beneficial to noninvasively know the exact degree of stenosis in the artery.

B-mode imaging measurements of the residual vessel lumen during CFDU evaluation are not very sensitive or specific when compared with angiographic evaluation.[8] Ultrasound artifacts such as shadowing from calcified plaque, vessel tortuosity, and the difficulty of the observer to accurately identify the edges of the luminal borders have made b-mode images less desirable to take luminal measurements.[9] The advent of color-flow in the 1980s made visualization of luminal blood flow easier; however, inherent artifacts with color-flow, including "bleeding" of the color signature outside of the vessel lumen, have also introduced flaws in the CFDU luminal measurement techniques.

Doppler interrogation also has inherent flaws. Because the technique depends on the skill of the individual performing the test, reproducibility may be problematic. The inability of the examiner to isolate the narrowest portion of the vessel, shadowing from calcified plaque, and inconsistent application of reliable angles make velocities unreliable in some cases.[10]

Because the CFDU evaluation uses Doppler derived peak systolic and end-diastolic velocity measurements to determine the degree of stenosis and the angiographic modalities use direct visualization of the residual vessel lumen, these parameters are not comparable.

In this study, a method of directly visualizing the residual lumen using b-mode ultrasound imaging was used to find the luminal diameter and then calculate diameter reduction, increasing the accuracy of the measurement. The formula used to calculate the diameter reduction is distal ICA diameter minus proximal ICA diameter divided by the distal ICA diameter (Figure 2). The reconstruction software (Visualize: Vascular™; Medipattern, Toronto, Canada) reveals the residual lumen of the vessel, stripping the other entire image content away to show a 3D rendering of the residual lumen only. The technology is able to distinguish the lumen or residual lumen from the vessel wall, plaque, or other lesions.

This technology uses pattern recognition to highlight regions of interest, such as the lumen in a vessel. Pattern recognition uses the grayscale, dynamic range, and contrast to determine the pattern within the image, identifying the interfaces between the lumen and its neighboring components to isolate only the lumen, which the human eye cannot readily differentiate on the B-mode images.

In this study, there was a statistically significant correlation between RDE and DDE, with only one vessel not correlating with the Doppler evaluation. This discrepancy was a case in which the 3D reconstruction found a 63% luminal ICA reduction but Doppler estimated the diameter reduction at 70–79%. The proximal ICA peak systolic velocity was recorded as 392 cm/sec and end-diastolic velocity at 158 cm/sec. Further review of the cine clip found that the transducer was not in contact with the patient at the end of the clip as seen in Figure 3. The software algorithm used the widest diameter noted in the clip; however, the distal cervical ICA was not fully appreciated, possibly underestimating the diameter reduction. It is important that the full length of the ICA be captured.

There were several other issues noted during the evaluation of the technique and the software. Although longitudinal sweeps were performed and evaluated in several cases, it was noted that the ultrasound beam may not be at the center point in the plane of the artery. This may lead to falsely narrow lumens as shown in Figure 4. It was determined that transverse sweeps were needed; however, transverse images in only one plane demonstrated drop out of the reflected ultrasound sound beam on the lateral walls as the result of reflection artifact, so it was decided that two planes perpendicular to each other were needed to properly build the image. This required diligence on the part of the technologist performing the exam. Thus, the time to technologist proficiency could be a factor.

The technologist performing the examination must have knowledge of the anatomy and assure that proper planes are obtained. The average time to perform the protocol on the patients enrolled in the study was 10 minutes bilaterally. It is projected that this time can be reduced as technologists become more comfortable with the technique.

Table 4

Results

Stenosis Category	Number of ICAs as Measured Using Velocity	Number of ICAs as Measured Using 3D Reconstruction
0–49%	66	66
50–69%	8	9
70–79%	2	1
80–99%	2	2
100%	1	1
Total	79	79

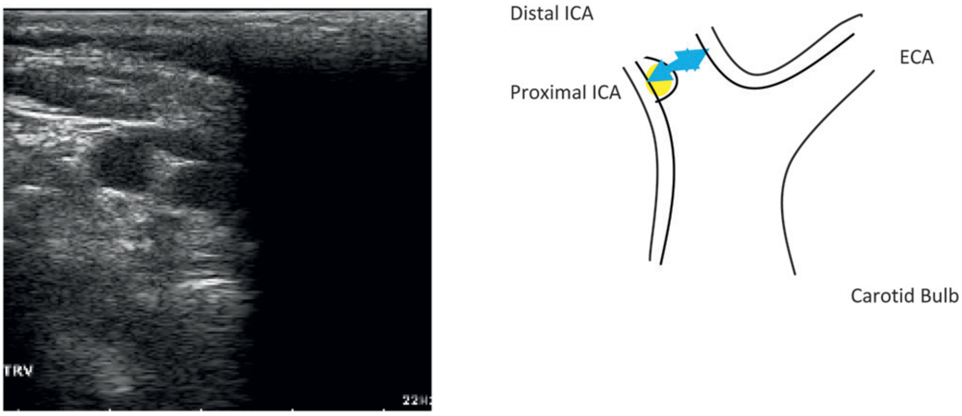

Figure 3

Discrepant case. Please note on the duplex image to the left the lack of signal on the right side of the image, indicating that the transducer has no contact with the skin surface.

Several methods of diameter measurement were used, including the methods similar to those described in the European Carotid Surgery Trial (ECST)[11] and the North American Symptomatic Carotid Endarterectomy Trial.[12] The European Carotid Surgery Trial method compares the true lumen of the vessel from intima to intima to the residual lumen; however, the software algorithm was not configured to determine the wall-to-wall diameter of the vessel at the time of this study. It was decided that the most reliable and reproducible method for the purposes of this study would be the North American Symptomatic Carotid Endarterectomy Trial method, which compares the narrowest diameter within the area of stenosis to the diameter of a segment of the ICA distal to the lesion. This method may be limited because the technologist may have difficulty imaging the distal ICA in certain circumstances.

This study showed 100% correlation between RDE and DDE when there was <50% ICA diameter reduction. On occasion, it was noted that there was a "negative" stenosis, by virtue that vessels with minimal atherosclerotic disease in the wider proximal cervical ICA was larger than the distal ICA used for comparison.

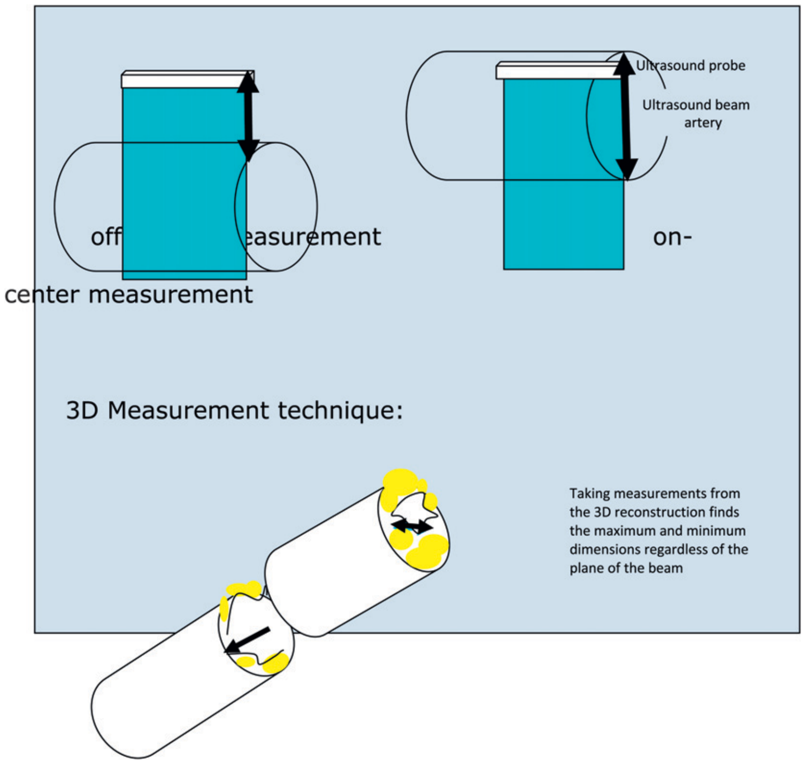

Figure 4

Comparing 3D to 2D measurement Techniques.

This study compared Doppler-derived diameter reduction estimates to lumen measurements generated by 3D reconstruction software. Although the 3D reconstruction images were not compared directly to other imaging studies like angiography, they were compared with Doppler criteria that were internally validated by comparisons to angiography. Further research will be needed to compare the 3D reconstruction technique to these other modalities. Recently the software has been expanded not only to determine the luminal diameter but to also obtain the cross-sectional area reduction. Further analysis will be forth coming.

Conclusion

3D reconstruction of the residual lumen in the ICA utilizing transverse motion ultrasound shows significant correlation with Doppler-derived diameter reduction measurements. Combining the 3D luminal reconstruction software with CFDU can give an accurate measurement of the degree of stenosis in the vessel. This may ultimately influence management decisions in patients with carotid artery disease. Although more investigation is needed, 3D reconstruction may be a valuable adjunct and may enhance the diagnostic capabilities of CFDU.

References

1. Schulte-Altedorneburg G, Drost DW, Felszeghy S, et al. Detection of carotid artery stenosis by in vivo duplex ultrasound: Correlation with planimetric measurements of the corresponding postmortem specimens. *Stroke* 2002;33:2402–2407.

2. Strandness DE. Clinical carotid measurements: Present and future state. *Tex Heart Inst J* 1982;9:177–184.

3. Shetty PG, Jhaveri KS. Neurovascular applications of CT angiography. *Indian J Radiol Imaging* 2000;10:211–220.

4. Grant EG, Benson CB, Moneta GL, et al. Carotid artery stenosis: Gray-scale and Doppler US diagnosis—Society of Radiologists in Ultrasound Consensus Conference. *Radiology* 2003;229:340–346.

5. Executive Committee for the Asymptomatic Carotid Atherosclerosis Study. Endarterectomy for asymptomatic carotid artery stenosis. *JAMA* 1995;273:1421–1428.

6. Lal BK. Sonographic evaluation in carotid artery stenosis. In: B. Schaller, ed. *Imaging of Carotid Artery Stenosis*. Austria: Springer Wein; 2007:35–40.

7. Thurnher SA. MRA of the carotid arteries. *Eur Radiol* 2005; 15(Supp 5):E11–E16.

8. Kozàkovà M, Morizzo C, Andreucetti F, Palchetti P, Parenti G, Palombo C. Quantification of extracranial carotid artery stenosis by ultrafast three-dimensional ultrasound. *J Am Soc Echocardiogr* 2001;14:1203–1211.

9. Mackenzie KS, French-Sherry E, Burns K, Pooley T. B-mode ultrasound measurement of carotid bifurcation stenoses: Is it reliable? *Vasc Endovasc Surg* 2002;36:123–135.

10. Bluth EI, Arger PH, Benson CB, Ralls PW, Siegel MJ. *Ultrasound: A Practical Approach to Clinical Problems.* New York: Thieme; 2005.

11. The European Carotid Surgery Trialists Collaborative Group. Risk of stroke in the distribution of an asymptomatic carotid artery. *Lancet* 1995;345:209–212.

12. Ferguson GG, Eliaszwi M, Barr HW, et al. The North American Symptomatic Carotid Endarterectomy Trial: Surgical results in 1415 patients. *Stroke* 1999;30:1751–1758.