A novel method to quantify carotid artery stenosis by Doppler ultrasound: Using the continuity principle

Christopher B Wong MD FACC¹, Joseph C Wong²

CB Wong, JC Wong. A novel method to quantify carotid artery stenosis by Doppler ultrasound: Using the continuity principle. *Int J Angiol* 2010;19(2):e86-e90.

BACKGROUND AND PURPOSE: A novel method to quantify carotid artery stenosis by using the continuity principle was evaluated. It was hypothesized that the novel method improved the accuracy of carotid ultrasound in assessing carotid artery stenosis.

METHODS: Forty-nine patients were retrospectively studied. They were at a high risk for stroke and myocardial infarction, with significant cardiovascular risk factors. They were studied by carotid ultrasound as well as by one of the accepted gold standard techniques (computed tomography, magnetic resonance imaging or angiography). The cross-sectional areas of the narrowed part of the carotid arteries

were measured using the continuity principle, and the percentage stenosis was thus calculated.

RESULTS: The analyses showed that the combination of the conventional and novel criteria (ie, classifying a case as significant only if its stenosis was 67% or greater and its peak systolic velocity was 130 cm/s or greater) conferred the highest accuracy in predicting significant carotid stenosis compared with the gold standard techniques.

CONCLUSION: From a practical point of view, the combined criteria might be useful for improving the accuracy of carotid ultrasound in predicting significant carotid stenosis.

Key Words: Carotid artery stenosis; Continuity principle; Doppler ultrasound

Stroke is a leading cause of death in the United States. Significant carotid artery stenosis is associated with stroke. Therefore, it is important to screen for significant carotid stenosis and to treat as early as possible. Clinical studies (1-3) have shown that a benefit was present with surgical intervention if the patients had carotid stenosis of more than 70% (by diameter measurement) on an invasive carotid angiogram. In symptomatic patients who had minor stroke-like symptoms, 25% of patients experienced a stroke within two years without surgery compared with 9% of patients who underwent carotid artery surgery. In patients without symptoms, a smaller benefit was seen in performing preventive carotid surgery. Doppler ultrasound remains an important, inexpensive and noninvasive tool to detect significant carotid stenosis. Other methods to detect and confirm the stenosis include computed tomography (CT), magnetic resonance imaging (MRI) and invasive carotid angiography. Carotid angiography has been considered the 'gold standard' in quantifying the degree of stenosis. The conventional way of determining the amount of carotid stenosis on ultrasound is by measuring the peak velocities across the narrowed carotid arteries (conventional or bulbar criteria). High velocities across the carotid narrowing correlated well with the stenosis diameter measured by invasive angiography (for example, a peak systolic velocity [PSV] of 250 cm/s or greater correlated with carotid narrowing of 70% or greater on invasive angiography). The conventional (bulbar) criteria are somewhat empirical. Different laboratories develop their own

velocity criteria on an individual basis to account for the differences in equipment. With the use of the mathematical continuity principle (ie, principle of conservation of mass) (4) – which states that in a nonbranched vessel, the volume of the blood flow within the narrowed segment is equal to the volume of blood flow through the normal segment – the cross-sectional area within the narrowed segment and percentage stenosis may be calculated accordingly. We, therefore, hypothesized that using the continuity equation (the 'novel' method) to calculate the percentage stenosis of the carotid artery on carotid ultrasound would demonstrate reasonable accuracy compared with the accepted gold standard techniques such as CT, MRI and invasive angiography. (In the present project, for practical purposes, CT, MRI and invasive angiography were all considered to be the accepted gold standard techniques.) We further hypothesized that the combination of the novel and conventional criteria would achieve the highest accuracy in detecting significant carotid stenosis compared with the gold standard techniques.

METHODS

A retrospective analysis of 49 consecutive patients from a community clinic was conducted. These patients were at a high risk for stroke and myocardial infarction, with significant risk factors such as hypertension, diabetes, a history of coronary artery disease, stroke, myocardial infarction and/or hyperlipidemia. They were studied using carotid ultrasound and one of the

¹Conroe Regional Medical Center, Conroe; ²The Woodlands College Park High School, The Woodlands, Texas, USA

Correspondence: Dr Christopher B Wong, Conroe Regional Medical Center, 100 Medical Center Boulevard, Suite 213, Conroe, Texas 77304, USA. Telephone 936-760-2544, fax 936-760-2545, e-mail Cbwong2007@yahoo.com

TABLE 1
Baseline demographic and clinical data (n=49)

Characteristic	Value
Age, years, mean $\pm$ SD	71 $\pm$ 9.9
Sex	
Male	26 (53)
Female	23 (47)
Smoking	22 (45)
Diabetes	21 (43)
Hypertension	49 (100)
Hyperlipidemia	48 (98)
History of coronary artery disease	38 (78)
History of myocardial infarction	10 (20)
History of stroke	15 (31)

Data presented as n (%) unless otherwise indicated

accepted gold standard techniques (ie, CT of the carotid arteries, MRI of the carotid arteries or invasive carotid angiography) between July 2007 and December 2009. The time interval between performing the carotid Doppler ultrasound and the gold standard technique was limited to 90 days. Demographics of the patients were obtained, including age and sex, and presence of hypertension, diabetes mellitus, high cholesterol level, myocardial infarction or stroke.

For carotid artery stenosis quantification, the cross-sectional areas of the narrowed part of the carotid arteries were obtained using the continuity principle:

$$A_1 \times V_1 = A_2 \times V_2$$

$$A_1 = (A_2 \times V_2)/V_1$$

where A_1 is the cross-sectional area of the narrowest segment, V_1 is the peak velocity of the narrowest segment, A_2 is the cross-sectional area of the distal reference segment and V_2 is the peak velocity of the distal reference segment. A_0 was designated as the original cross-sectional area at the level of the narrowest segment if there had been no plaque formation.

The percentage area stenosis was calculated using the following equation (equation 1):

$$(1 - [A_1/A_0]) \times 100\%$$

$$\text{ie, } (1 - [D_2 \times D_2 \times V_2]/[D_0 \times D_0 \times V_1]) \times 100\%$$

where D_0 is the original diameter at the narrowest segment with no plaque formation and D_2 is the luminal (open-spaced) diameter of the distal reference segment.

Correlations were calculated between the degree of narrowing of the carotid arteries as measured by gold standard techniques versus measurements with different methods (ie, the novel method using PSV, the traditional method using conventional criteria, and using velocity ratios of the proximal and distal carotid arteries).

Statistical analysis

Correlation of angiographic stenosis and other Doppler measurements was expressed by linear regression analysis with Pearson's product moment correlation coefficient r as a measure of goodness of fit. Statistical significance was evaluated by Student's t test (two-tailed). $P < 0.05$ was considered to be statistically significant.

TABLE 2
Carotid ultrasound results and diameter stenoses using gold standard techniques

	Value
D_0 (the original diameter at the level of the narrowest segment if there had been no plaque formation), cm	0.93 $\pm$ 0.21
D_2 (the diameter of the distal reference segment lumen), cm	0.6 $\pm$ 0.16
V_1 (PSV of the narrowest segment), cm/s	178 $\pm$ 85
V_2 (PSV of the distal reference segment), cm/s	109 $\pm$ 50
Velocity ratio using PSVs of the proximal and distal internal carotid arteries	2.1 $\pm$ 1.7
Velocity ratio using VTI (proximal and distal internal carotid arteries)	2.2 $\pm$ 2.9
Stenosis (diameter) of the carotid arteries using one of the gold standard techniques, %	63 $\pm$ 18
Stenosis (diameter) of the carotid arteries using conventional (bulbar) criteria, %	69 $\pm$ 12
Stenosis (area) of the carotid arteries using novel criteria (continuity equation) and PSVs, %	70 $\pm$ 15
Stenosis (area) of the carotid arteries using novel criteria (continuity equation) and VTI, %	67 $\pm$ 19

Data presented as mean $\pm$ SD. PSV Peak systolic velocity; VTI Velocity-time integral

Figure 1 Correlation between the degree of narrowing of the carotid arteries measured using the novel method (percentage area stenosis using peak systolic velocity [PSV]) and using a gold standard technique (percentage diameter stenosis)

RESULTS

Data from 49 patients with complete carotid Doppler examinations and results from one of the gold standard tests (ie, CT, MRI or carotid angiography) were analyzed.

Demographics are presented in Table 1. The mean ($\pm$ SD) patient age was 71 $\pm$ 9.9 years (range 49 to 87 years). A high percentage of patients had coronary artery disease (78%), diabetes (43%), hypertension (100%), stroke (31%), myocardial infarction (20%) and hyperlipidemia (98%), making the group a high-risk population.

Table 2 showed the results of the measurements: the carotid artery dimensions, systolic velocities across the narrowing and across the distal reference segments, percentage stenosis calculated by different methods, and velocity ratios of the proximal and distal internal carotid arteries.

Figures 1 to 3 show the correlation between the degree of narrowing of the carotid arteries measured by the gold standard method versus the percentage stenosis measured by different

Figure 2) Correlation between the degree of narrowing of the carotid arteries measured using the conventional method (percentage diameter stenosis using conventional/bulbar criteria) and using gold standard techniques (percentage diameter stenosis)

Figure 3) Correlation between the degree of narrowing of the carotid arteries measured by velocity ratio (proximal and distal internal carotid artery [ICA] velocity ratio) and using gold standard techniques (percentage diameter stenosis). PSV Peak systolic velocity

methods (ie, the novel method [PSV], traditional method using conventional criteria, and velocity ratios of proximal and distal carotid arteries). The graphs show that the correlation coefficients were acceptable using the novel and traditional methods ($r=0.69$ and $r=0.64$ respectively, $P<0.001$), but the correlation coefficients were low ($r=0.43$ and $r=0.49$) using velocity ratios methods.

Table 3 shows the sensitivities, specificities, positive predictive values, negative predictive values and accuracies for various Doppler criteria to predict 70% or greater stenosis using gold standard techniques. It was shown that by using a PSV of 130 cm/s as a cut-off, the sensitivity of the test was high (96%) but the specificity was limited (44%). On the other hand, by using a PSV of 250 cm/s as a cut-off, the specificity of the test was high (100%) and the sensitivity was very limited (39%).

The accuracies for a stenosis area of 67% or greater as a cut-off using the novel method to predict 70% or greater stenosis using gold standard techniques conferred a high sensitivity (96%) but a limited specificity (67%). However, the combined criteria (ie, classifying a case as significant only if its stenosis was 67% or greater, and its PSV was 130 cm/s or greater) offered the highest accuracy for predicting 70% or greater stenosis using gold standard techniques, with a high sensitivity (96%), and an acceptable specificity (81%) and accuracy (88%).

TABLE 3
Sensitivity, specificity, positive predictive value (PPV), negative predictive value (NPV) and accuracy for different Doppler criteria compared with gold standard tests

Bulbar criteria	PSV ≥ 130 cm/s, n	PSV < 130 cm/s, n
Gold standard test, +	22	1
Gold standard test, -	15	12
Sensitivity = 96%, PPV = 59%, specificity = 44%, NPV = 92% and accuracy = 68%		
Bulbar criteria	PSV ≥ 250 cm/s, n	PSV < 250 cm/s, n
Gold standard test, +	9	14
Gold standard test, -	0	27
Sensitivity = 39%, PPV = 100%, specificity = 100%, NPV = 66% and accuracy = 72%		
Novel criteria	Novel method (stenosis area $\geq 67\%$), n	Novel method (stenosis area $< 67\%$), n
Gold standard test, +	22	1
Gold standard test, -	9	18
Sensitivity = 96%, PPV = 71%, specificity = 67%, NPV = 95% and accuracy = 80%		
Combined criteria	+ Combined criteria, n	- Combined criteria, n
Gold standard test, +	22	1
Gold standard test, -	5	22
Sensitivity = 96%, PPV = 81%, specificity = 81%, NPV = 96% and accuracy = 88%		
Velocity ratio criteria	Velocity ratio ≥ 1.6 , n	Velocity ratio < 1.6 , n
Gold standard test, +	15	8
Gold standard test, -	7	20
Sensitivity = 65%, PPV = 68%, specificity = 74%, NPV = 71% and accuracy = 70%		
Velocity ratio criteria	Velocity ratio ≥ 5.0 , n	Velocity ratio < 5.0 , n
Gold standard test, +	3	20
Gold standard test, -	0	27
Sensitivity = 13%, PPV = 100%, specificity = 100%, NPV = 57% and accuracy = 60%		

- Negative; + Positive; PSV Peak systolic velocity

Finally, the accuracies of the velocity ratios of the proximal and distal carotid arteries in predicting 70% or greater stenosis were low: 70% accuracy when the ratio 1.6 was used, and 60% accuracy when the ratio 5.0 was used.

DISCUSSION

Many studies (5,6) have shown that carotid Doppler ultrasound is a good screening test to detect carotid stenosis compared with the gold standard techniques. The conventional method was to use the bulbar criteria, which are considered to be empirical and crude. The bulbar criteria make use of the Bernoulli principle with the following simplified equation:

$$PG = 4V^2$$

where PG is the pressure gradient across the narrowed artery and V is the velocity across the narrowed artery. For example, if the PSV across the narrowed artery was 2.5 m/s, then the pressure gradient would be 25 mmHg.

In general, a pressure gradient of greater than 20 mmHg responded to significant narrowing. The above method has been used in clinical practice for many years but, nevertheless, different laboratories have had to develop their own criteria based on the available gold standard techniques to account for the differences in equipment.

It was found that the percentage stenosis measured by gold standard techniques correlated statistically ($P < 0.001$) with percentages measured by different methods (ie, the novel method using PSV, the traditional method using conventional criteria, and velocity ratios of the proximal and distal carotid arteries). However, the table showing sensitivities, specificities, positive and negative predictive values, and accuracies (Table 3) clearly demonstrated that the percentage stenosis obtained by the combined criteria was superior to that obtained by either method, with a very high sensitivity, and a reasonable specificity and accuracy. On the other hand, both methods conferred a high sensitivity but a limited specificity. This was not a surprising result because the combined criteria made full use of two mathematical principles in physics in setting up the criteria, ie, the continuity principle and the Bernoulli principle. This potentially increased the accuracy of the results.

The least accurate test in the study was the method using the velocity ratios. This occurrence may have been due to the fact that the distal and proximal diameters were not taken into account. In a highly tapered carotid artery in which the proximal carotid segment is much wider than the distal artery, the percentage stenosis obtained by velocity ratio would be erroneous according to the following equation:

$$\% \text{ area stenosis} = 1 - (D_2^2/D_0^2) \times (V_2/V_1)$$

D_2/D_0 would be unacceptably low in a highly tapered carotid artery, making the V_2/V_1 ratio obsolete as an acceptable method to detect significant stenosis.

Few studies in the current medical literature used the continuity principle to calculate the percentage stenosis. In the studies by Popa et al (7) and Ranke et al (8), the authors claimed that the continuity principle was used but, in fact, only the velocity ratios, not the diameters, were taken into account.

In the current study, the traditional criteria using 250 cm/s as a velocity cut-off offered a good specificity (100%) but a poor sensitivity (39%) in predicting carotid stenosis of 70% or greater using one of the gold standard techniques. The exact reasons were unclear. Apparently, other clinical studies (5,6) in the medical literature showed a higher accuracy with the traditional criteria test. A possible reason was that the large clinical validation studies were performed in academic medical centres. These results may not be reproducible in a community clinic setting.

Limitations

First, the present study was retrospective; therefore, it suffers from limitations conferred by its retrospective style. The studies were conducted some time ago; therefore, the technician may not have paid enough attention to accurately measure the dimensions of the carotid artery that were required in the current study. It was not a blinded study; therefore, the principal scientist may have been biased.

There were also technical limitations in the current study. Distal radius dimensions were difficult to measure when the distal carotid artery was very tortuous. Also, if error occurred in the diameter measurements, the error would be magnified due to the 'squared' effect, as shown in the equation of percentage area stenosis (equation 1). The diameter D_0 could have been

difficult to measure if there were calcified, irregular plaques obscuring the true lumen (space) of the carotid artery.

It was assumed that the shape of the cross-sectional carotid artery was circular, but in reality, it was not necessarily so because of the inherent characteristics of the vessel or plaque buildup inside the vessel wall.

Another limitation of the current study is the fact that the imaging was performed by one technician in a community clinic setting. It is unclear whether the results are reproducible in other medical settings because carotid Doppler ultrasound is a technician-dependent imaging method. The skills of each technician may potentially affect the results. Also, the analysis was made by two observers only. It is desirable for more trained individuals to analyze the images to account for interobserver differences. Moreover, the number of patients undergoing the analysis was small (49 patients). One of the reasons was that not many patients during that period had one of the gold standard techniques performed and, therefore, they were not included in the present study. Despite these shortcomings, the positive results we obtained were encouraging and it was expected that with more patients in the cohort, the results would be further supported.

Finally, the gold standard techniques chosen in the current study may not be the 'true' gold standards. For practical purposes, invasive studies, such as carotid angiography, are avoided in many clinical settings. Therefore, MRI and CT have been accepted as so-called gold standard techniques. It has been shown in some studies (9) that MRI may be inferior to CT and carotid angiography in depicting carotid stenosis accurately.

CONCLUSION

Based on the above analysis, it was demonstrated that by using the continuity principle (ie, the novel method), the percentage stenosis of the carotid arteries thus calculated correlated well with the results obtained by one of the gold standard techniques (ie, carotid angiography, CT or MRI). The combination of the conventional and novel criteria (ie, classifying a case as significant only if stenosis was 67% or greater and PSV was 130 cm/s or greater) conferred a high accuracy in predicting a 70% or greater carotid arterial stenosis by gold standard techniques. A potential application might be incorporating the combined criteria in a software program in future ultrasound machines to help doctors make sound clinical decisions. Further larger prospective studies are required to validate the superiority of the combined criteria before widespread use takes place in daily medical practice.

REFERENCES

1. Barnett HJ, Taylor DW, Eliasziw M, et al. Benefit of carotid endarterectomy in patients with symptomatic moderate or severe stenosis. North American Symptomatic Carotid Endarterectomy Trial Collaborators. *New Engl J Med* 1998;339:1415-25.
2. Chambers BR, Donnan GA. Carotid endarterectomy for asymptomatic carotid stenosis. *Cochrane Database Syst Rev* 2005;(4):CD001923.
3. Moneta GL, Edwards JM, Chitwood RW, et al. Correlation of North American Symptomatic Carotid Endarterectomy trial (NASCET) angiographic definition of 70% to 99% internal carotid artery stenosis with duplex scanning. *J Vasc Surg* 1993;17:152-9.
4. Libby P, Bonow RO, Zipes DP, Mann DL, eds. *Braunwald's Heart Disease: A Textbook of Cardiovascular Medicine*, 8th edn. Philadelphia: Saunders/Elsevier, 2008:264.

5. Braun RM, Bertino RE, Milbrandt J, Bray M. Ultrasound imaging of carotid artery stenosis: Application of the Society of Radiologists in Ultrasound Consensus Criteria to a single institution clinical practice. *Ultrasound Q* 2008;24:161-2.
 6. Jahromi AS, Cinà CS, Liu Y, Clase CM. Sensitivity and specificity of color duplex ultrasound measurement in the estimation of internal carotid artery stenosis: A systematic review and meta-analysis. *J Vasc Surg* 2005;41:962-72.
 7. Popa VN, Spencer MP, Lion CL, Felberg RA. 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. *Stroke* 2007;38:1780-5.
 8. Ranke C, Creutzig A, Becker H, Trappe HJ. Standardization of carotid ultrasound: A hemodynamic method to normalize for interindividual and interequipment variability. *Stroke* 1999;30:402-6.
 9. Patel MR, Klufas RA, Kim D, Edelman RR. MR angiography of the carotid bifurcation: Artifacts and limitations. *AJR Am J Roentgenol* 1994;162:1431-7.
-