Background and Purpose—All carotid stenosis ratio methods are based on the inability of digital subtraction angiography to measure in millimeters. Each method has potential flaws. The Carotid Stenosis Index (CSI) was designed to reduce ambiguities of NASCET and ECST ratios. We test this method’s ability to correctly estimate carotid stenosis using direct computed tomography angiography millimeter measures of the carotid arteries.

Methods—Two neuroradiologists reviewed computed tomography angiographies of 268 carotids with atherosclerotic disease. Millimeter measurements were obtained at the narrowest diameter of the residual stenotic lumen, actual carotid bulb diameter (at level of greatest stenosis), and common carotid artery. Pearson correlation compared the CSI estimate of the carotid bulb to the actual carotid bulb measurement. Ratio calculations of the stenosis were performed using (1) CSI carotid bulb estimate and (2) actual carotid bulb measurement as denominator data. A paired-sample Wilcoxon signed rank test compared the results of these 2 ratio measurements per carotid.

Results—Interobserver variability was good to excellent (0.64 to 0.87). The CSI estimate of the carotid bulb size overestimated the measured carotid bulb by an average of 1.5 mm in a random distribution (correlation = 0.39, N = 151). Paired-sample Wilcoxon signed rank test demonstrated a significant difference between the 2 sets of ratios (z-value of -9.87, P < 0.001).

Conclusions—Direct measurement of carotid stenosis, vessel wall soft tissues, and computed tomography plaque imaging is now possible with the high-resolution anatomic data present in high-speed computed tomography angiography, alleviating the need for ratios and inaccurate mathematic estimations of carotid anatomy for carotid stenosis quantification. (Stroke. 2007;38:286-291.)

Key Words: angiography ■ carotid stenosis ■ CT ■ CT angiography ■ imaging ■ neuroradiology ■ radiology

Carotid stenosis assessment has evolved with new advances in computed tomography imaging technology.1–3 For years, the methodology of carotid stenosis quantification was debated, especially after publication of original results from the largest randomized trials regarding carotid stenosis and carotid endarterectomy, NASCET and ECST trials.4,5 These trials relied on indirect ratio methods, because direct measurements of carotid stenosis were impossible with catheter angiography and digital subtraction imaging (DSA), now possible with computed tomography angiography (CTA).4–7

Both NASCET and ECST trials used the narrowest measured stenosis as the numerator. NASCET used the distal internal carotid artery (ICA) as the denominator, whereas ECST used the estimated diameter of unseen outer walls of the stenosed ICA bulb. Because the ICA bulb is nearly twice the diameter of distal ICA, these 2 ratio methods resulted in very different percentage stenosis for the same carotid.7,8 Thus, initial results of NASCET and ECST trials4,5 varied for severe stenosis and stroke rates for particular percentage stenosis, creating ambiguities regarding ratio calculation and therapeutic decision-making.

Both ratio methods have their own intrinsic flaws creating the potential for serious errors. Errors with the NASCET ratios reflect the challenge of identifying subtle near occlusions and congenitally narrow distal ICAs, and varying compliance of measuring the distal ICA where the walls are parallel (instead of tapering carotid bulb).3,9 Errors in ECST ratios reflect the subjective bias of measuring an unseen artery. These ambiguities generated interest in other methods of carotid stenosis quantification based on catheter DSA.

The Common Carotid method and the Carotid Stenosis Index (CSI) were created to alleviate ambiguities of NASCET and ECST methods.8,10,11 Advocates of these methods state that the use of the common carotid artery (CCA) as
denominator data might be more reliable for stenosis calculation.\textsuperscript{8,10,11} This is based on the reported ease of distal common carotid artery visualization on catheter DSA, usually without overlying vessels, and on its alleged "disease-free" state.\textsuperscript{8,10,11}

Despite attempts at novel ratio methods, ambiguities remain regarding carotid stenosis quantification and ultimately regarding proper therapeutic decision-making. As imaging technologies advanced, alternatives to catheter DSA such as magnetic resonance angiography, Doppler ultrasound, and early CTA were intensively studied.\textsuperscript{12–22} Nonetheless, these modalities all refer to catheter DSA and NASCET and ECST trials as standards to base their quantification methods as percentage stenosis, most often to NASCET.

Carotid stenosis quantification with current high-speed multidetector CT/CTA differs from all other methods, including catheter DSA. Specifically, CTA allows direct millimeter measurement of contrast-filled vessels (diseased and normal) and surrounding noncontrast-filled soft tissues in the neck.\textsuperscript{1} Although CTA exposes the patient to ionizing radiation (like in DSA), CTA irradiates far less than multivessel selective DSA, is quick and easy to perform, provides more information than all other imaging techniques, and does not have DSA stroke risk. At this time, DSA retains an advantage over CTA as a result of its time-resolved nature providing the direction and sequence of contrast flow within arteries and veins that is useful to assess filling of arteriovenous malformations and fistulas.

The advantages of CTA created a new measurement paradigm for carotid stenosis quantification. A recent study correlated the direct CTA carotid stenosis millimeter measurements of 268 carotids with their corresponding NASCET ratios.\textsuperscript{1} This study published cutoff values for moderate and severe carotid bulb stenosis at 2.2 mm and 1.3 mm, respectively.\textsuperscript{1}

The purpose of this study is to analyze the accuracy of the CSI technique by applying this method to CTA of the carotid arteries. Although the CSI method never became a dominant carotid stenosis quantification tool, its assumptions create an opportunity to show the benefits of direct CTA measurements over mathematical estimates of vessel diameter.\textsuperscript{1–3} Ultimately, we highlight the ability of current high-resolution CTA to directly quantify carotid stenosis, alleviating the need for ratio calculations.

![Image](image-url)

### Materials and Methods

#### Patients/Subjects

Subjects were retrospectively collected from a single institution using an AGFA Impax 4.5 (Mortsel, Belgium) PACS database from August 2003 through March 2004. Inclusion criteria included all consecutive patients with a history of known or suspected carotid artery atherosclerotic disease. Exclusion criteria included trauma, dissection, vascular anomaly/malformation, per-/postoperative studies unrelated to carotid atherosclerotic disease, cases primarily evaluating posterior circulation, inadequate coverage, and/or technical errors precluding full evaluation of cervical carotid arteries. The study was approved by our center’s research ethics board (Project identification no. 411-2004). Informed consent was not required for inclusion in this study and its evaluation of records and images.

#### Materials/Image Acquisition

All CTA examinations were performed using a GE Medical Systems Lightspeed Plus 4-slice helical CT. Images were obtained from C6 to vertex using the helical HS mode with 7.5 mm/rotation and 1.25×1.25-mm collimation (120 kVp, 350 mA). Intravenous access was through an antecubital vein using an 18- or 20-gauge angiocatheter. A total of 100 to 125 cc Omnipaque 300 was injected at a rate of 4.0 to 4.5 cc/second with a 17-second delay or use of Smart Prep at the pulmonary artery.

Postprocessing multiplanar reformats (MPRs) were created at the CT operator’s console. Coronal and sagittal MPR images were created 10.0 mm thick spaced by 3 mm. Bilateral rotational MPRs were created at the carotid bifurcations with a thickness of 7 mm and spacing by 3 mm. Three-dimensional rendered images were created on a GE Advantage Workstation. All images were viewed on AGFA Impax 4.5 PACS workstations.

#### Image Analysis/Interpretation

Two neuroradiologists, in a blind protocol, independently reviewed all cases meeting inclusion criteria. The reviewers surveyed each carotid artery by simultaneously using axial source images with MPR images to define the following areas of interest: (1) residual stenotic carotid bulb lumen at its narrowest diameter, (2) assume carotid bulb diameter at the level of greatest stenosis, and (3) medial carotid artery (3 to 5 cm inferior to carotid bifurcation).\textsuperscript{10} The actual carotid bulb diameter was measured from inner wall to inner wall on the opposite side. The “inner wall” measures only the lumen, apart from soft tissue walls, and corresponds to the contrast-filled lumenogram within a nondiseased vessel. The different densities of vessel wall and plaque allow CTA measurement of the actual carotid bulb diameter (lumen) despite atherosclerotic vessel disease.

Millimeter measurements were obtained using submillimeter measurement and magnification tools on the PACS workstation (Figure 1) as described in earlier works regarding quantification of carotid arteries with CTA.\textsuperscript{1–3} No specific Window/Level settings were prescribed for image analysis. Instead, each reviewer modified these settings to better depict the residual stenotic ICA lumen, the actual ICA walls, and to decrease beam-hardening artifact from dense calcifications. In general, the Window/Level settings were quite wide, progressing to very wide settings in the cases of dense calcifications (usually around W2093:L792). Narrower Window:Level settings exaggerate the size of the densely contrast-filled lumens and calcified plaque, obscuring actual vessel walls.

The narrowest carotid bulb stenosis and the common carotid artery lumen were measured by manually placing the measurement calipers at edges of contrast-filled lumenograms (Figures 1 and 2). Direct measurements of actual carotid bulb were obtained from the inner wall to the opposite inner wall (actual vessel lumen) (Figure 1). All measurements were obtained from axial images. Arteries identified by MPRs as oblique to the axial plane were measured perpendicular to their oblique axis in the axial plane to obtain the narrowest diameter and not an exaggerated oblique diameter. These measurements were verified with measures from reformats to ensure accuracy in obtaining the narrowest diameter in a true cross-sectional plane.\textsuperscript{1}

Mathematic estimates of the carotid bulb diameter were calculated according to the CSI method, which relied on previously published anatomic relationships between the CCA and the carotid bulb (ICA to CCA ratio as 1:1.19 [±0.09]).\textsuperscript{10–11} The CSI authors rounded off to simplify the ICA to CCA relationship with the following equation: \(1.2 \times \text{CCA diameter} = \text{CSI carotid bulb estimate}.\) The CSI stenosis ratio was calculated with CSI carotid bulb estimate (CSI estimate) as the denominator\textsuperscript{10} according to the following equation: \(1−(\text{narrowest stenosis diameter/CSI estimate})\times100.\) The CSI estimate was calculated using the direct CCA diameter measurement for each carotid.\textsuperscript{10}

#### Statistical Methods

All raw data were analyzed using the statistical software package, SPSS for Windows (version 12.0.0; Chicago, IL). A \(P\) value <0.01
indicated a statistically significant difference. All missing data were
excluded pairwise from calculations.
Correlation coefficients (Pearson product moment) were calcu-
lated with 2-tailed significance to evaluate interobserver agreement
for all measurements. Pearson product moment correlation evaluated
the relationship between the direct carotid bulb measurement and the
CSI estimate of the carotid bulb.
Ratios of carotid bulb stenosis were calculated per carotid (1−narrowest
diameter stenosis/direct measure versus CSI estimate of
carotid bulb diameter)\(\times 100\), with the following as the denominator
data: (1) direct carotid bulb measurement and (2) CSI estimate of
carotid bulb diameter.
A paired-sample Wilcoxon signed rank test was performed to
compare results of these 2 methods of ratio calculation per carotid.
The null hypothesis states that there is no difference between carotid
bulb stenosis ratios calculated with (1) direct carotid bulb measure-
ment and (2) CSI estimate of carotid bulb diameter.

**Results**
Two neuroradiology reviewers evaluated 268 carotid arteries
that met inclusion criteria (134 CTA cases). The reviewers
showed excellent interobserver agreement between their nar-owest stenosis diameters with a correlation coefficient of
0.87 (\(N=179\)). The interobserver agreement was good for
direct carotid bulb diameter and for CCA diameter with
correlation coefficients of 0.64 (\(N=151\)) and 0.67 (\(N=261\),
respectively.
Given the low interobserver variability, measurements
from the 2 reviewers were averaged to obtain mean stenosis,
mean carotid bulb, and mean CCA measurements.
Mean CCA measurements were used to calculate the
mathematical estimate of the carotid bulb (CSI bulb) accord-
ing to the CSI method (Figure 3). The CSI bulb calculation
produced an average estimated diameter of 7.86 mm
(\(N=261\); standard deviation=1.25; range=4.0 to 15.5). This
is in comparison to mean direct carotid bulb average of
6.41 mm (\(N=151\); standard deviation=1.05; range=3.8 to
8.9). The CSI bulb overestimated direct bulb diameter 89.4%
(135 of 151) of the time, averaging 1.5 mm larger than direct
bulb measurements. There were 3 cases in which the CSI bulb
estimation and direct bulb measures were equal (2.0% [3 of
151]) with the remaining 8.6% (13 of 151) of the CSI bulb
estimations representing underestimations of the direct bulb
diameter. The correlation between the direct bulb measures
and the CSI bulb estimation was randomly distributed (cor-
relation coefficient of 0.39 [\(N=151\)]).
Comparison of the ratio calculations, using the CSI esti-
mate and direct measurements as the denominator, showed
that the CSI ratio overestimated direct bulb ratio 91.4% (138
of 151) of the time. There was a single tie between a CSI
A paired-sample Wilcoxon signed rank test rejected the null hypothesis regarding the CSI ratio and direct bulb ratio calculations \(z\text{-value} = -9.87, P < 0.001\). The alternate hypothesis was accepted, stating there is a statistically significant difference between the ratios generated from the CSI method and the direct bulb measurement method (Figure 3).

**Discussion**

**Direct CTA Measurements and CT Plaque Imaging**

With the exception of direct carotid bulb measurement, all axial CTA measurements were of contrast-filled luminograms just as for catheter DSA. However, CTA vessel measurements are obtained on the axial plane. This is an advantage when measuring the narrowest diameter, because it takes at least 2 separate planes with catheter DSA to determine whether the residual stenotic lumen is asymmetric.

Direct measurement of the carotid bulb, from inner wall to inner wall including any plaque, is a departure from traditional diameter measures done with CTA, magnetic resonance angiography, and catheter DSA. This measurement requires the interpreter to identify the actual carotid bulb wall, not just the contrast-filled lumen. CTA is the only current angiographic method that allows such high-resolution images of contrast-filled vessels, plaque, and surrounding soft tissues.21

Measurement of noncontrast-enhanced soft tissues is not without its challenge. Not only does the vessel wall need to be identified, but it needs to be separated from adjacent calcifications and plaque. Plaque has variable density, most likely related to various fatty, hemorrhagic, fibrous, and calcified components. Nonetheless, the vessel wall typically has a higher density than the intraluminal plaque as well as the fatty tissues surrounding the vessel.

In the case of very coarse wall calcifications, properly wide Window:Level settings can reduce beam-hardening artifacts so that the residual contrast-filled lumen, plaque, and the noncalcified vessel wall can be confidently evaluated. In our study, the vast majority of very coarse wall calcifications were asymmetric and did not involve the entire carotid bulb wall, allowing for vessel wall measurements in areas of the vessel not affected by the calcifications.

The vessel walls were not sharply conspicuous from their plaque contents in a total of 6 carotid bulbs: 3 carotids with circumferential coarse calcifications and 3 carotids with absence of normal fatty tissue planes surrounding the carotid bulb. Cases with circumferential coarse wall calcifications were associated with very severe stenosis with a residual lumen less than 1.0 mm corresponding to greater than 70% stenosis by NASCET criteria. Despite difficulty with quantification in such cases, CTA still has an advantage over other imaging techniques by defining the morphology of the calcification, which may have implications regarding treatment strategy.

Although the interobserver agreement of the direct carotid bulb diameter measurements was good, with a correlation...
coefficient of 0.64 (N = 151), the variability was higher than measurement of the narrowest stenosis (0.87 [N = 179]). This highlights the challenges of CTA identification of the vessel wall. Nonetheless, the CSI bulb estimate overestimated the direct measurement of the actual carotid bulb diameter by an average of 1.5 mm. This overestimation is not likely the result of systematic undermeasurement of the direct carotid bulb, because the correlation between the direct measures and CSI bulb estimates was randomly distributed with a correlation coefficient of 0.39 (N = 151).

CSI Ratios Revisited
CCA is not “disease-free” in patients with atherosclerotic disease. We found that plaque was common within CCA, even 3 to 5 cm inferior to the carotid bifurcation (Figure 4). Because CTA also images the soft tissues adjacent to the contrast-filled lumen, subtle plaque can be detected. Such subtle findings on catheter DSA could be missed without the presence of associated coarse calcifications, ulcer, or other secondary findings.

The CSI method uses a fixed conversion factor of 1.2 to estimate the carotid bulb size based on a “fixed anatomic relationship” between the CCA and the carotid bulb. Other authors report the relationship between these vessels is far from fixed with standard deviations ranging from ±0.09 in one study to ±0.19 in another. In another study of 1001 carotid bifurcations, the average CCA to ICA ratio was 1.0 with a range of 0.7 to 1.4. CCA contrast luminograms have variations, just like all other vessels, and should not be used to estimate the diameter of other vessels (Figure 4).

Stenosis Quantification Revisited
Until recently, all stenosis quantification was based on indirect methods of measurement that relies on various ratio and mathematical schemes to standardize between cases. NASCET, ECST, CSI, and the Common Carotid method all measure the same stenosis; however, each “translates” the stenosis into its own “standards” based on the mathematics of each respective ratio calculation. The relationship between these methods is essentially linear, thereby allowing data to be converted between methods.

Direct CTA millimeter measurement of carotid stenosis is yet another method to quantify stenosis. The advantage of CTA is that measurement of stenosis, as well as of other structures, is direct and does not need standardization between patients by mathematical conversions.

Conclusion
Direct measurement of vessel diameter is possible with high-resolution anatomic data present in high-speed CTA. This applies to the contrast-filled luminograms of normal and diseased vessels as well as the actual soft tissue vessel wall. With such direct, high-resolution imaging, cumbersome ratio calculations using visual or mathematic estimates of vessel diameter are not necessary.

Disclosures
None.

References

Figure 4. CCA atherosclerotic disease and CSI method. a, Coronal MPR of left CCA and carotid bifurcation. b, Axial of left CCA (white dashed box) 3 to 5 cm inferior to carotid bifurcation. Narrowest diameter of diseased CCA (C) = 0.33 cm (3.3 mm). Arrow points to actual CCA wall surrounding residual lumen and low-density plaque. c, Three-dimension of left CCA with ulcerated plaque (small arrow)


