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Semi-Automated Computer Assessment of the Degree of Carotid Artery Stenosis Compares Favorably to Visual Evaluation

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Abstract

OBJECTIVE—To validate a semi-automated computer approach for the assessment of the degree of carotid artery luminal narrowing by comparing it to the visual evaluation by a neuroradiologist.

STUDY DESIGN AND MAIN OUTCOME MEASURES—In a retrospective cross-sectional study, consecutive emergency department patients who underwent computed tomography angiography (CTA) of the carotid arteries were identified. CTA studies were reviewed by a neuroradiologist, and also independently processed with a computer algorithm that automatically measures the degree of luminal narrowing at the level of the internal carotid artery bulb. The findings of the neuroradiologist and computer assessment were compared using Chi2 tests/kappa calculations and linear regression for categorical and continuous measurements of carotid stenosis, respectively.

RESULTS—The study population consisted of 125 patients (74 no stroke/TIA, 18TIA, and 33stroke). 201 carotid arteries showed no significant stenosis; 33 showed $\geq 70\%$ stenosis, 5 showed 95–99% stenosis, and 11 showed complete occlusion. There was excellent agreement between the neuroradiologist's visual assessment and the automated computer evaluation of the category of carotid stenosis (kappa=0.918, $p < 0.001$).

CONCLUSION—The automated computer algorithm for quantifying the degree of carotid stenosis is reliable and shows high concordance with the interpretation of an experienced neuroradiologist.

Introduction

Carotid artery atherosclerotic disease occurs frequently in the general population, with a prevalence of 75% in men and 62% in women over 64 years of age^{1,2}. The standard parameter used to describe the extent and severity of carotid artery disease is the degree of luminal narrowing. This comes from several randomized clinical trials, including the North American Symptomatic Carotid Endarterectomy Trial (NASCET)^{3,4} and the European Carotid Surgery Trial (ECST)^{5,6}, which demonstrated a reduction in the risk of ischemic stroke in patients with a luminal stenosis of $\geq 70\%$ after carotid endarterectomy, compared with medical treatment alone. The degree of luminal narrowing has been traditionally measured on catheter angiography^{7,8}; however it is increasingly being measured using noninvasive techniques such as Doppler ultrasound, CT-angiograms (CTA) or MR-angiograms (MRA)^{9,10}. These have

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been shown to be equivalent to conventional angiograms in characterizing the degree of luminal narrowing^{9, 11, 12}.

Measuring the degree of luminal narrowing using CTA or MRA raises some issues in the clinical setting. First, several methods have been reported to characterize the degree of carotid stenosis, including the NACSET method³⁴, the ECST method^{5, 6}, and the common carotid method¹³, which differ as to the reference arterial segment used resulting in different percent measurements for the same absolute residual lumen.^{13–16} Also, different visualization methods (maximal intensity projection (MIP), volume rendering, surface-shaded display (SSD)) are available for the display of the same dataset^{12, 17–21}, adding to the variability of the luminal narrowing measurements. Furthermore, inter-observer variability results since, in typical clinical practice, neuroradiologists simply “eyeball” the carotid artery lumen and only obtain quantitative measurements in a limited number of cases. The highest precision in measuring carotid stenosis is known to be attained by using magnified axial images and by getting measurements exactly perpendicular to the longitudinal axis of the vessel^{10, 21}; this, however, is time-consuming and is rarely performed in the routine clinical practice. Finally, the measurement of the luminal narrowing is influenced by the image quality, and particularly by the quality of the contrast injection.²²

Recently, software has become available on post-processing workstations that performs semi-automatic segmentation of the carotid artery lumen on CTA studies, and automatic quantitative measurements of diameter and area. This approach could potentially alleviate some of the limitations listed above, but the use of such software has not yet been validated.

The goal of this paper is to validate a semi-automated computer assessment of the degree of carotid artery luminal narrowing by comparing it to the visual evaluation by an experienced neuroradiologist.

Methods

Patients

All consecutive patients admitted to the Emergency Department (ED) between July 2005 and December 2005, who underwent a CTA of their carotid arteries were retrospectively identified. This retrospective, cross-sectional study was approved by our institutional review board. In order to be eligible for the study the patients had to undergo a follow-up brain imaging study (either CT or MRI) after the ED CTA, in order to make a final diagnosis of stroke or absence thereof, and to determine the side of the stroke if one existed. Patients were excluded if: (1) They had an intracranial hemorrhage, or (2) they had a hemispheric stroke prior to the considered admission, as evident from either the clinical history or imaging.

After review of the follow-up brain imaging studies and the medical records, the patients were separated into two groups: patients who had a diagnosis of stroke, and those who did not. Among the non-stroke patients, those with a clinical diagnosis of transient ischemic attack (TIA) at discharge were also considered separately. For the stroke and the TIA groups, the side of the event was recorded, as determined by history and physical examination on admission in the ED (for TIA patients) and by follow-up brain imaging studies (for stroke patients).

CTA Imaging Acquisition Protocol

The CTA studies were obtained on a 16-slice CT scanner (General Electric Medical Systems, Milwaukee, WI, US). The image acquisition protocol was as follows: spiral mode, 0.6-second gantry rotation, collimation: 16×1.25 mm, pitch: 1.375:1, slice thickness: 1.25 mm, reconstruction interval: 1.00 mm, acquisition parameters: 120 kVp/240 mA. A caudo-cranial scanning direction was selected, covering from the mid-chest to the vertex. Seventy milliliters

(mL) of Iohexol (Omnipaque, Amersham Health, Princeton, NJ; 300 mg/mL of iodine) was injected to an antecubital vein with a power injector at a rate of 4 mL per second. Adequate timing of the CTA acquisition was achieved using a test bolus technique.

Visual Assessment of CTA Studies by the Neuroradiologist

A CAQ-certified neuroradiologist with more than five years' experience after a 2-year fellowship reviewed the CTA studies and assessed them for the maximal degree of stenosis in the right and left internal carotid arteries according to the NASCET method.

Specifically, the reviewer was asked (1) to quantify the degree of carotid stenosis and (2) to assign the patients to one of the following four categories: no significant stenosis (<70%), significant stenosis ($\geq 70\%$), subocclusion (95–99%), or complete occlusion (100%).

The reviewer was blinded to the prior interpretation of the images and to the patients' clinical condition. The review was performed on a post-processing workstation where the reviewer could look at the raw axial CTA images and obtain multiplanar reformats (MPR) and MIPs in multiple planes. The post-processing workstation was equipped with a caliper tool to perform measurements. The reviewer was instructed to proceed exactly as is done in the reading-room for routine cases. Typically, this involves eyeballing the degree of carotid stenosis on 3-mm thick MIP images of the carotid bifurcations obtained in the coronal and sagittal oblique planes, and confirming this result on raw axial CTA images using caliper measurements.

Semi-Automated Evaluation of CTA Studies by the Computer Algorithm

CTA studies of the carotid arteries were exported off-line to a separate PC computer and processed independently, using dedicated, custom-developed, Matlab (The MathWorks, Inc., Novi, MI)-based software, by a second neuroradiologist, also blinded to the prior interpretation of the images and to the clinical condition of the patients. The role of the second neuroradiologist was to identify and place 'seeds' within the lumen of the common carotid artery and the internal carotid artery, on each side. Based on these seeds, the software automatically segmented the lumen of the carotid artery and measured (perpendicular to the main direction of the lumen): (1) the minimal absolute diameter and (2) the minimal absolute area of the internal carotid artery at the level of the maximal bulb stenosis, as well as the average diameter and the average area of the distal cervical internal carotid artery. The NASCET percent of narrowing was calculated for the diameter (3) and a similar measurement was obtained for the area (4). This process was performed separately for the right and left carotid arteries.

In the case of total occlusion of the internal carotid artery, the neuroradiologist could not place seeds and the software could not be used to measure the degree of stenosis. In such cases, the minimal absolute diameter and the minimal absolute area of the internal carotid artery at the level of the maximal stenosis in the bulb were assumed to be zero; the NASCET percent of narrowing was 0% for both the diameter and the area.

Comparison between visual assessment by the neuroradiologist and semi-automated computer evaluation of the degree of carotid stenosis

For the degree of luminal narrowing, we compared the exact degree of stenosis from visual assessment by the neuroradiologist with: the percent of diameter stenosis, the percent of area stenosis, the minimal absolute diameter, and the minimal absolute area. Bland-Altman plots between the visual assessment and the five automated computer measurements were computed. Linear regression was also performed.

For the categories of carotid stenosis (no significant stenosis ($<70\%$), significant stenosis ($\geq 70\%$), subocclusion (95–99%), complete occlusion (100%)), we compared the assignation based on the neuroradiologist's visual assessment with the automated computer measurements using Chi2 tests and unweighted kappa calculations.

Results

Patients

The study population consisted of a consecutive series of 125 patients (250 carotid arteries) admitted to the Emergency Department of our institution between July 2005 and December 2005, who underwent a CTA on admission to evaluate their carotid arteries and who satisfied the inclusion and exclusion criteria listed in the methods section. Of the 125 patients studied, 76 (52.8%) were female and 59 (47.2%) were male. The mean age was approximately 64 years old (standard deviation: 17.5, minimum: 20, maximum: 92).

Seventy-four patients were categorized as having no stroke or TIA (most of these patients had a final diagnosis of syncope of unknown origin, migraine or hypoglycemia), 18 as having a TIA, and 33 as having a stroke. Of the 51 patients with either TIA or stroke, 24 were left hemispheric events and 27 were right.

CTA Imaging Studies

Of 125 CTA studies, three bolus injections were considered to be suboptimal because of poor contrast injection bolus. In these three cases, the CTA studies were still interpretable and no significant narrowing was diagnosed either by the neuroradiologist or by the computer algorithm.

Visual Assessment of CTA Studies by the Neuroradiologist

The 250 carotid arteries in the 125 patients of the study were categorized by the neuroradiologist as follows: 201 (80.4%) were classified as having no significant stenosis ($<70\%$); 33 (13.2%) were classified as having significant stenosis ($\geq 70\%$); 5 (2.0%) were classified as being subocclusive (95–99%); 11 (4.4%) were classified as having complete occlusion (100%).

The exact degree of stenosis as measured by the neuroradiologist in each category of stenosis is reported in Table 1.

Semi-Automated Computer Evaluation of CTA Studies

The exact degree of stenosis as determined by the computer algorithm is reported in Table 1.

Comparison between visual assessment by the expert neuroradiologist and semi-automated computer evaluation of the degree of carotid stenosis

The results of the categorical classification of the 250 carotid arteries in the study by the neuroradiologist and by the computer algorithm, are reported below in Table 2 (for the computer algorithm, this analysis is based only on the derived percent of diameter narrowing). There was excellent agreement between the expert neuroradiologist's visual assessment and the semi-automated computer evaluation of the category of carotid stenosis, with a kappa value of 0.918, a chi2 of 609.5 and a p value < 0.001 . There was perfect concordance for the cases of complete occlusion.

Results of the linear regression analysis between the exact degree of stenosis from the neuroradiologist's visual assessment and the automated computer measurements are reported in Table 3. There was excellent correlation between the expert neuroradiologist's visual

evaluation, and both the percent of diameter narrowing and the percent of area narrowing as assessed by the computer algorithm, with excellent coefficients of determination R^2 , slopes nearly equal to 1, and intercepts close to 0. The negative slopes for the values of absolute diameter and area narrowing are explained by the inverse relationship to the degree of luminal narrowing: as the degree of narrowing increases, the absolute diameter and area of the lumen decrease.

A Bland-Altman plot displaying the relationship between the expert neuroradiologist's visual assessment and the percent of diameter narrowing from the automatic computer assessment is presented in Fig. 1. Despite the overall agreement between the neuroradiologist and computer algorithm in the evaluation of the degree of carotid stenosis, there was better agreement for high degrees of stenosis than for low degrees of stenosis. Low degrees of stenosis (well below 70%, the threshold for clinically significant stenosis) tended to be disregarded by the expert neuroradiologist, whereas the computer evaluation showed that there is actually considerable variability in the degree of narrowing in this category of mild stenosis. The stepwise appearance of points on the graph is due to the fact that the expert neuroradiologist rounded the degree of stenosis to the nearest 5%.

Discussion

In typical clinical practice, the standard parameter reported to describe the severity of carotid artery disease is the degree of luminal narrowing. CTA has been shown to be a reliable substitute to conventional angiography in the estimation of the degree of carotid stenosis.²³ The degree of luminal narrowing is typically visually assessed by the radiologist interpreting the study.

In this retrospective cross-sectional analysis involving 125 patients, we demonstrated that a semi-automated computer algorithm was able to quantify the degree of carotid luminal narrowing, and that this analysis performed similarly to an experienced neuroradiologist in interpreting the CTA images and characterizing the severity of carotid stenosis. This is in agreement with previous reports describing other similar semi-automated methods currently available.^{24, 25}

The agreement between the neuroradiologist and the computer algorithm, with respect to evaluation of the category of carotid stenosis, was excellent (κ value = 0.918, $p < 0.001$).

The best correlations were found between the neuroradiologist's visual assessment and the computer evaluation of percent of diameter narrowing (slope = 0.95, intercept = 0.03, $R^2 = 0.984$, $p < 0.001$) and percent of area narrowing (slope = 0.96, intercept = 0.04, $R^2 = 0.976$, $p < 0.001$). For each category of luminal narrowing (<70%, ≥70%, 95–99%, 100%), the software found a greater percent of area narrowing than percent of diameter narrowing. This is because diameter narrowing is a linear measurement in mm while area narrowing is a cross-sectional measurement in mm^2 , giving it a larger value for the degree of narrowing. The percent of area narrowing has the advantage that it can accurately account for irregular luminal morphology and eccentricity^{26,27} whereas diameter measurements are only reliable if the luminal cross-section is circular.

There was perfect concordance for complete carotid occlusions. Again, in cases of total occlusion of the internal carotid artery, the software used could not measure the degree of stenosis, and the minimal absolute diameter and area of the internal carotid artery at the level of the maximal stenosis in the bulb were assumed to be zero, explaining the perfect agreement that was observed.

Despite the overall agreement between the expert neuroradiologist and computer algorithm in the evaluation of the degree of carotid stenosis, there was greater agreement for high degrees of stenosis than for low degrees of stenosis. Low degrees of stenosis (well below 70%, the threshold of clinical significance) tended to be disregarded by the neuroradiologist, whereas the computer evaluation showed that there is actually a considerable variability in the exact degree of narrowing in this category of mild stenosis.

In conclusion, using a semi-automated computer algorithm for quantifying the degree of carotid stenosis is reliable and shows high concordance with the interpretation of an experienced neuroradiologist. This kind of computer algorithm could potentially increase the reproducibility and improve the standardization of the carotid narrowing measurements.

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Fig. 1. Bland-Altman plot displaying the relationship between the expert neuroradiologist's visual assessment and the percent of diameter narrowing from the semi-automatic computer assessment.

Table 1

Degree of stenosis from the neuroradiologist's visual assessment and the semiautomated computer evaluation's determination of percent of diameter stenosis, percent of area stenosis, minimal absolute diameter, and minimal absolute area, in the four categories of carotid stenosis as assessed by the neuroradiologist

		Expert Neuroradiologist Visual Assessment, Categories of Carotid Stenosis			
		<70% n=201	≥70% n=33	95-99% n=5	100% n=11
Expert Neuroradiologist Visual Assessment, Degree of Carotid Stenosis	mean	6.5%	84.4%	96.2%	100.0%
	SD	15.4%	6.8%	1.6%	0.0%
	min	0.0%	75.0%	95.0%	100.0%
	max	74.0%	93.0%	98.0%	100.0%
Semi-Automated Computer Evaluation, % Diameter Narrowing					
	mean	10.0%	85.3%	96.1%	100.0%
	SD	14.1%	5.6%	2.1%	0.0%
	min	0.0%	73.6%	92.9%	100.0%
	max	75.3%	95.1%	98.9%	100.0%
Semi-Automated Computer Evaluation, % Area Narrowing					
	mean	13.1%	86.8%	98.0%	100.0%
	SD	14.7%	7.0%	1.2%	0.0%
	min	0.0%	76.4%	96.5%	100.0%
	max	75.7%	95.9%	99.6%	100.0%
Semi-Automated Computer Evaluation, Minimal Absolute Diameter Narrowing [mm]					
	mean	4.13	0.60	0.11	0.00
	SD	0.09	0.24	0.10	0.00
	min	1.55	0.32	0.09	0.00
	max	6.92	1.07	0.26	0.00
Semi-Automated Computer Evaluation, Minimal Absolute Area Narrowing [mm2]					
	mean	15.83	1.19	0.19	0.00
	SD	6.06	0.44	0.25	0.00
	min	4.63	0.63	0.03	0.00
	max	49.89	2.03	0.52	0.00

Table 2
Comparison of categorical classification by the neuroradiologist and by the computer algorithm
Expert Neuroradiologist Visual Assessment, Categories of Carotid Stenosis

Semi-Automated Computer Evaluation, Categories of Carotid Stenosis	Expert Neuroradiologist Visual Assessment, Categories of Carotid Stenosis			
	<70% n=201	≥70% n=33	95-99% n=5	100% n=11
<70%	197	1	0	0
≥70%	4	31	1	0
95-99%	0	1	4	0
100%	0	0	0	11

Table 3

Results of the linear regression analysis between the exact degree of stenosis from the neuroradiologist's visual assessment and the automated computer measurements

Expert Neuroradiologist Visual Assessment, Categories of Carotid Stenosis

	slope	intercept	R2	p value
<i>Semi-Automated Computer Evaluation, % Diameter Narrowing</i>	0.95	0.03	0.984	<0.001
<i>Semi-Automated Computer Evaluation % Area Narrowing</i>	0.96	0.04	0.976	<0.001
<i>Semi-Automated Computer Evaluation, Minimal Absolute Diameter Narrowing [mm]</i>	-4.36	4.41	0.826	<0.001
<i>Semi-Automated Computer Evaluation, Minimal Absolute Area Narrowing [mm2]</i>	-17.16	16.91	0.495	<0.001