Stroke

American Stroke Association.

A Division of American Heart Association

Three-Dimensional Ultrasound Study of Carotid Arteries Before and After Endarterectomy : Analysis of Stenotic Lesions and Surgical Impact on the Vessel

Jiefen Yao, Marc R. H. M. van Sambeek, Anita Dall'Agata, Lukas C. van Dijk, Micheala Kozakova, Peter J. Koudstaal and Jos R. T. C. Roelandt

The online version of this article, along with updated information and services, is located on the World Wide Web at:

http://stroke.ahajournals.org/cgi/content/full/29/10/2026

Three-Dimensional Ultrasound Study of Carotid Arteries Before and After Endarterectomy
Analysis of Stenotic Lesions and Surgical Impact on the Vessel

Jiefen Yao, MD; Marc R.H.M. van Sambeek, MD; Anita Dall'Agata, MD; Lukas C. van Dijk, MD; Micheala Kozakova, MD; Peter J. Koudstaal, MD, PhD; Jos R.T.C. Roelandt, MD, PhD

Background and Purpose—It has been proved that symptomatic patients with severe carotid stenosis benefit from endarterectomy. Currently used methods for quantitation of the severity of carotid stenosis have limitations, and the impact of endarterectomy on the operated region of carotid artery remains unknown. The purpose of this study was to examine the accuracy of a 3-D ultrasound system for quantitation of stenotic lesions and to evaluate changes in regional vessel volume and cross-sectional area after carotid endarterectomy.

Methods—We studied 14 patients with both carotid angiography and 3-D ultrasound. Of 13 patients who underwent surgery, 12 were reexamined with 3-D ultrasound after surgery. The length and volume of 20 randomly selected plaques were measured from 3-D data sets. The severity of stenosis was quantified by 3-D ultrasound using both a diameter method and an area method on cross-sectional views at the most stenotic site; the results were then compared with those from carotid angiography. The segmental vessel volume and average cross-sectional area of the operated artery both before and after endarterectomy were measured from 3-D ultrasound data.

Results—Good correlation was obtained between 3-D ultrasound and carotid angiography in quantitative analysis of carotid stenosis (SEE=12.4%, $r=0.76$, and mean difference=$7.0\pm12.3\%$ with the diameter method; SEE=10.5%, $r=0.82$, and mean difference=$1.8\pm10.5\%$ with the area method by 3-D ultrasound). 3-D ultrasound had excellent reproducibility and small intraobserver and interobserver variability in plaque length and volume measurements. No significant changes in segmental vessel volume and average cross-sectional area of the operated artery were observed after surgery in patients with suture closure. However, a significant increase in segmental vessel volume was obtained in patients with polyfluorethylene patches applied to the surgical opening of the artery.

Conclusions—3-D ultrasound can be used for both qualitative and quantitative analysis of plaques in the carotid artery and to detect and quantify significant carotid stenosis. Its volumetric potential has important clinical implications in serial follow-up studies for observing the progression or regression of stenotic lesions and for evaluating the outcome of interventional procedures such as endarterectomy or stent placement. (*Stroke*. 1998;29:2026-2031.)

Key Words: atherosclerosis ■ carotid arteries ■ carotid endarterectomy ■ carotid stenosis ■ ultrasonography

It has been proved that symptomatic patients with severe carotid artery stenosis ($\geq70\%$) benefit from endarterectomy.[1–2] Selection of candidates for surgery is based mainly on carotid angiography.[3–6] Because of the invasiveness and the associated complications and mortality of this technique, noninvasive procedures have been used for evaluating the severity of carotid artery stenosis.[7–22] 2-D ultrasound scanning, in combination with Doppler, has been used either as an adjuvant or as the decisive examination for surgical candidate selection.[11–16] One of the major limitations of the 2-D method is that it requires mental reconstruction of the shape of the plaque and the stenotic vessel lumen from limited cross-sectional views. The 3-D reconstruction technique has been investigated in carotid artery imaging employing various modalities and has demonstrated some encouraging findings.[23–26] Whether volume-rendered 3-D ultrasound reconstruction could allow better appreciation of the stenotic

lesions and accurate assessment of the severity of stenosis of the cervical carotid artery is not known. Neither is the impact of endarterectomy on the volumetric properties of the regional carotid artery fully understood.[27] We have used a prototype 3-D vascular ultrasound reconstruction system to evaluate its reproducibility in the measurement of plaque length and volume and its value in quantitative assessment of the severity of stenosis compared with angiography. The changes in segmental vessel volume and average cross-sectional area of the carotid artery before and after endarterectomy were evaluated as well.

Subjects and Methods

Patients

In this study, we recruited 14 patients (4 females; mean age, 64 years; range, 41 to 77 years), each with a recent transient ischemic

attack or minor stroke. Carotid angiography showed at least 1 severe stenosis ($\geq$70%) of the carotid artery. All were considered candidates for carotid endarterectomy. We performed 3-D ultrasound of both carotid arteries within 3 months of carotid angiography or less than 3 weeks before surgery (baseline study). Thirteen of these patients underwent carotid endarterectomy, and 3-D ultrasound of the operated artery was repeated in 12 patients within 1 week after surgery (postoperative study). Informed consent for this study was obtained from each patient.

Carotid Artery Angiography

Selective carotid artery angiography was performed in a standard manner with use of the Seldinger technique. Each carotid artery was imaged from multiple projections. All angiograms were reviewed by an experienced independent observer to assess the site and severity of carotid artery stenosis with the method used in the European Carotid Surgery Trial.[1] A decrease of $\geq$50% of the estimated original lumen was defined as significant stenosis; severe stenosis was diagnosed when the lumen diminishment was $\geq$70%.

Carotid Endarterectomy

Carotid endarterectomy was performed in the classic way.[28–29] During the procedure, the cerebral perfusion was monitored with electroencephalography (EEG). A shunt was used only on indication of ischemia, when the EEG became asymmetric. After exposure and clamping, the artery was dissected longitudinally to expose the lumen, and the intima-media complex of the stenotic segment was excised. After close examination to ascertain that there was no debris left in the lumen, the artery was primarily closed with a running suture. In case the operated segment was of small diameter, the incision was closed with use of a polytetrafluorethylene patch to prevent the lumen from being too narrowed.

3-D Ultrasound of Carotid Arteries

Instrumentation

A commercially available ultrasound system (AU3 Partner, Esaote Biomedica, SpA) incorporated with a prototype probe was used for 3-D imaging of the carotid arteries. The prototype probe has a linear array transducer operating at dual frequencies of 10/7.5 MHz. The transducer is encased inside the probe, surrounded by mineral oil (Shell Cassida Fluid HF 16) as the transmission media. The fan-like movement of the transducer is steered by a stepper motor inside the probe controlled by the ultrasound system. The intervals between 2D images during data acquisition are programmable. The range of transducer movement can be predetermined at 30° to 65°. A prism 3-D ultrasound data set is acquired by automatic sequential collection of images in a push-button manner, with the probe held in a fixed position. 2-D images can be collected consecutively without ECG gating to produce a static data set, or a dynamic data set can be obtained by registration of ECG-gated images to their correspondent cardiac phases. The probe also has the ability of conventional 2D and spectral and color Doppler imaging.

Data Acquisition and Processing

In each patient, both carotid arteries were imaged before endarterectomy, and the operated artery was imaged after surgery. We first performed 2D ultrasound imaging and color and spectral Doppler to select the optimal acoustic window for 3-D data acquisition. The internal carotid artery was differentiated from the external carotid artery by their morphology (eg, the enlargement of the internal carotid artery at the bulb), their spatial relationship (judged from their positions in the imaging sector with known location of the probe), and the characteristics of the spectral Doppler from these vessels. This information was used later as well, in 3-D data analysis. A multitude of 2-D images of the carotid artery were collected sequentially at 1° intervals by steering the transducer through 65° without ECG gating. This process took less than 2 seconds. The acquired images were stored in a digital format and were simultaneously processed by the incorporated computer software within the ultrasound unit. The gaps between the 2-D images were interpolated with a bilinear algorithm to produce a volumetric 3-D data set, which
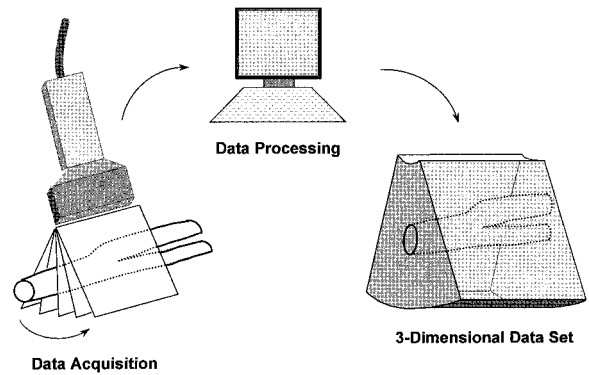

Figure 1. Schematics showing the principle of 3-D ultrasound data acquisition and production of a volumetric data set of the carotid artery.

was stored for off-line analysis (Figure 1). The 3-D data set was reconstructed with a reference system relative to the alignment of the probe. Any cross section selected through the volumetric data set was computed nearly in real-time. Images of the 2D ultrasound before and during 3-D data acquisition were stored onto VHS videotapes for necessary review.

Data Analysis

The 3-D data sets were reviewed by an independent observer unaware of angiographic results to determine the presence or absence of plaques and the site of stenosis. Measurement of plaque length and volume and severity of stenosis were performed separately by 2 blinded observers and repeated by one of them with intervals of 1 week or longer.

By moving the cutting plane through the 3-D data set in various directions, multiple views of the carotid artery were produced. The length of a plaque was measured in a longitudinal view of the vessel. By defining both ends of the plaque, multiple (as many as 20) equidistant cross-sectional cutting planes perpendicular to the longitudinal view of the plaque were generated automatically. The volume of the plaque was computed automatically from manual tracing of its borders on each cross-sectional image using a "summation of discs" method. The severity of stenosis was computed from measurements on the cross-sectional image with the smallest free lumen area with the following 2 methods. With the diameter method, the severity of stenosis was derived from measurements of the smallest free lumen diameter and the diameter of the original vessel lumen. With the area method, it was derived from the cross-sectional free lumen area and the original vessel lumen area (Figure 2).
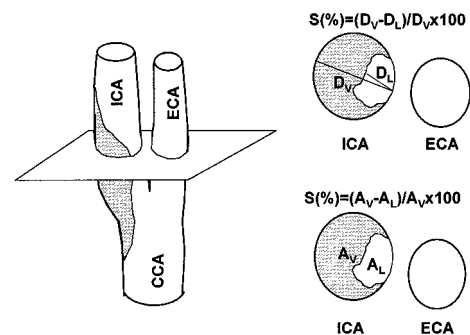
Figure 2. Schematic description of the diameter method and the area method for measuring the severity of carotid stenosis on the cross-sectional image reconstructed from a 3-D ultrasound data set. ICA indicates internal carotid artery; ECA, external carotid artery; CCA, common carotid artery; S, stenosis; D_L, minimal diameter of the free lumen; D_V, diameter of the original vessel; A_L, minimal area of the free lumen; and A_V, cross-sectional area of original vessel.
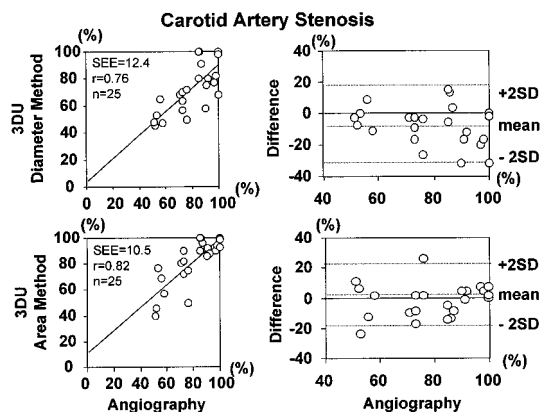
Figure 3. Linear regression (left) and Bland-Altman analysis (right) between the severity of carotid stenosis measured from angiography and that from 3-D ultrasound using the diameter method (top) and the area method (bottom).

In patients who underwent carotid endarterectomy, segmental vessel volume of the carotid artery bifurcation was measured before and after surgery. A longitudinal cutting plane of the carotid artery bifurcation showing the common, internal, and external carotid arteries was selected as a reference image from the 3-D data set. A 20-mm segment of the vessel, including 10 mm of the common carotid artery proximal and 10 mm of both internal and external carotid arteries distal from the bifurcation, was defined. Twenty parallel equidistant cross-sectional images of this segment were automatically generated, with each slice 1 mm in thickness. The area

Figure 4. A, Comparison between intraobserver (top) and interobserver (bottom) measurements of the lengths of 20 randomly selected plaques. B, Comparison between intraobserver (top) and interobserver (bottom) volume measurements of 20 randomly selected plaques.
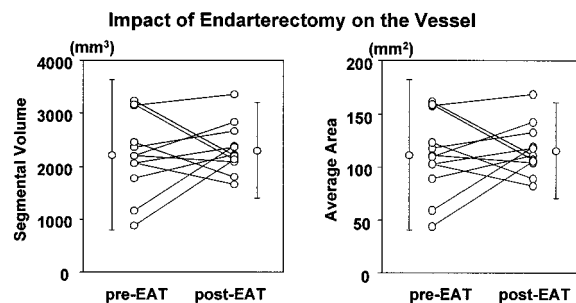
Figure 5. Graphs showing changes in segmental vessel volume (left) and average cross-sectional area (right) of the carotid artery before endarterectomy (pre-EAT) and after (post-EAT). Since the lengths of all the measured segments were the same (2 cm), the changes in segmental volume and in cross-sectional area are proportional.

of the carotid artery within the adventitia, ignoring any plaques if present, was traced manually on each slice to derive the segmental vessel volume. Divided by the predefined length of the segment (20 mm), an average cross-sectional area of the carotid bifurcation was also computed.

Statistics

All data were expressed as mean±SD. Comparison between measurements by 3-D ultrasound and angiography before and after surgery and intraobserver and interobserver variability were examined using linear regression, paired Student *t* test, and Bland-Altman analysis. A value of $P<0.05$ was defined as statistically significant.

Results

Carotid Endarterectomy

Endarterectomy was successful in all 13 patients who underwent this procedure. Among the 12 patients who had 3-D ultrasound both before and after surgery, 3 required intraoperative shunts, 3 had polytetrafluoroethylene patches on closure of the arterial incision, and 2 suffered from postoperative bleeding that required reoperation within 24 hours after surgery. There was no other major perioperative event.

Carotid Artery Angiography

In all 14 patients, 26 significant stenoses (5% to 100%, 82±17%) were found in 19 of 28 examined vessels by carotid artery angiography. Eight of these stenoses were located in internal, 8 in external, and 1 in common carotid arteries, and 9 were at the bifurcation extending from common to internal carotid artery. Of these stenoses, 21 were severe (≥70%).

3-D Ultrasound of the Carotid Artery

3-D ultrasound was performed in all 14 patients in baseline studies and in 12 patients in postoperative studies. In baseline studies, 3-D data sets were obtained from both left and right carotid arteries; for the postoperative studies, 3-D data sets of the operated carotid artery were obtained. It took less than 2 seconds to acquire each data set.

Carotid Stenosis

All the significant stenoses diagnosed from angiography were recognized from 3-D ultrasound except 1 in the external carotid artery (due to suboptimal image quality). The severity of stenosis measured from 3-D ultrasound ranged from 45% to 100% (74±19%) using the diameter method and 40% to
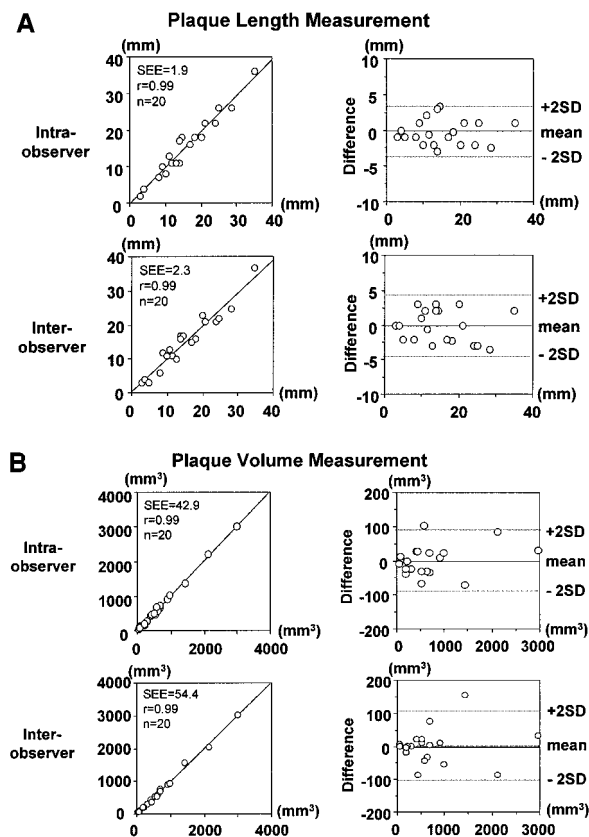
100% (83±18%) using the area method. The correlation between the percentage of stenosis measured from angiogram and that measured from 3-D ultrasound using the area method (SEE=10.5%, r=0.82, mean difference=1.8±10.5%) was better than that using the diameter method (SEE=12.4%, r=0.76, mean difference 7.0±12.3%) (Figure 3). The sensitivity, specificity, positive predictive value, and negative predictive value of 3-D ultrasound in defining severe carotid stenosis were 65%, 100%, 100%, and 65%, respectively, using the diameter method, and 90%, 92%, 95%, and 86%, respectively, using the area method.

Plaques
From 3-D ultrasound data sets of the carotid artery, the length and volume of 20 randomly selected plaques were measured. They ranged from 3 to 35 mm (15±8 mm) in length and 45 to 2980 mm³ (703±734 mm³) in volume. There was excellent correlation for both intraobserver and interobserver measurements (Figures 4A and 4B).

Surgical Impact
At the most stenotic site, the cross-sectional area of the carotid artery free lumen changed from 6.4±6.3 mm² before endarterectomy to 50.6±18.8 mm² after. The segmental vessel volume and the average cross-sectional area of the operated artery (2 cm long, including the bifurcation) changed on average from 2227 mm³ (874 to 3240 mm³) and 111 mm² (44 to 162 mm²) before surgery to 2318 mm³ (1648 to 3368 mm³) and 115 mm² (82 to 168 mm²) after surgery, with a slight but nonsignificant increase (Figure 5). By dividing the patients into a group with patches applied during surgery and a group without patches, a significant increase was observed in the segmental volume in the former group. In the latter group of patients without patches, the segmental volume had no significant change, although the average value slightly decreased (Figure 6).

Additional Information
Besides the quantitative information of the carotid artery and stenotic lesions, we were able to obtain some incremental information of the carotid artery, plaques, and surrounding structures from 3-D ultrasound. Not only the longitudinal but also the circumferential extent of the plaque was well appreciated at various levels. The eccentricity of the plaque distribution and the cross-sectional area and shape of the free vessel lumen were better portrayed throughout the segment of the carotid artery that was within the 3-D data set (Figure 7). Presence or absence of calcification in the plaque or the vessel wall could be predicted from the intensity of the ultrasound signal in comparison with surrounding tissues, with the calcified plaques or vessel wall appearing brighter and usually causing shadowing or ultrasound attenuation.

Discussion

Imaging Techniques for the Carotid Artery
Among the techniques that have been used for evaluation of carotid artery stenosis, angiography is the most widely used and accepted for selection of candidates for carotid endarterectomy, as it was in the North American Symptomatic Carotid Endarterectomy Trial (NASCET) and the European Carotid Surgery

Trial (ECST).[1–6] However, carotid angiography is an invasive procedure with nonnegligible complications and peri-procedural risk, especially in patients with severe stenosis.[7–8,30–31] Besides, the technique provides exclusively free lumen projections, ignoring details of the plaques, the vessel wall, and the surrounding tissues and structures. Therefore, the assessment of the percentage of carotid artery narrowing at the stenotic site requires either extrapolation of the original diameter of the vessel lumen at the same site (ECST) or measurement of vessel diameter at a reference site, such as the segment of the vessel distal to the stenosis (NASCET) or the common carotid artery.[1–6,32] Experience with intravascular ultrasound in carotid artery imaging is still preliminary.[33] Although it may provide information about the arterial wall and stenotic lesions on cross-sectional views, it gives less information on the longitudinal extension of the lesions. Besides its invasiveness and expense, intravascular ultrasound is limited in use in severe carotid stenosis. MR angiography and CT angiography of the carotid artery have been investigated as well.[17–22] Both techniques are expensive and neither is available at bedside. The latter also requires contrast injection. Therefore, their application is limited in daily practice. 2D ultrasound is able to overcome some of the drawbacks of the above-mentioned techniques and has proved reliable in some previous studies in the evaluation of carotid artery stenosis, especially when combined with Doppler imaging.[11–16] However, its feasibility and accuracy has been challenged by the physical inaccessibility of some cutting planes, which in some circumstances might be crucial for diagnosis. In addition, 2D ultrasound is technically operator dependent in the acquisition of the useful on-line information. 3-D ultrasound imaging of the carotid arteries has brought the attention of clinical workers to its potential use.[23–24,34]

3-D Ultrasound of the Carotid Artery
3-D surface ultrasound, realized by sequential collection of 2-D images of the carotid artery, results in a volumetric digital data set. The method we used in this study has several advantages. First, it is noninvasive and portable and can be performed in various clinical settings. Second, it may minimize the discomfort
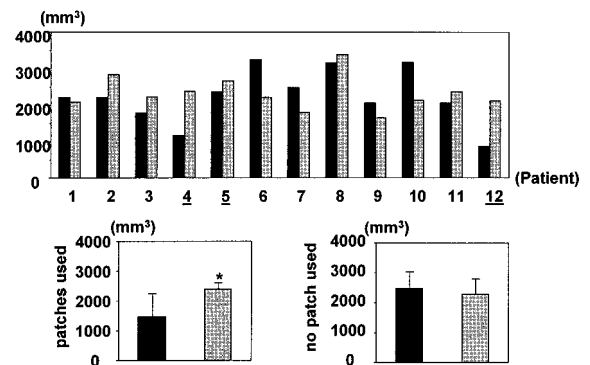
Figure 6. Plots showing changes of segmental vessel volume at baseline (black bars) and postoperative (gray bars) in each individual patient (top) and in the groups of patients with (bottom left) and without (bottom right) polytetrafluorethylene patches during endarterectomy on closure of the artery. Patches were applied in patients 4, 5, and 12 (underlined). The postoperative segmental vessel volume in the group of patients with patches had significant increase compared with baseline measurement (*).
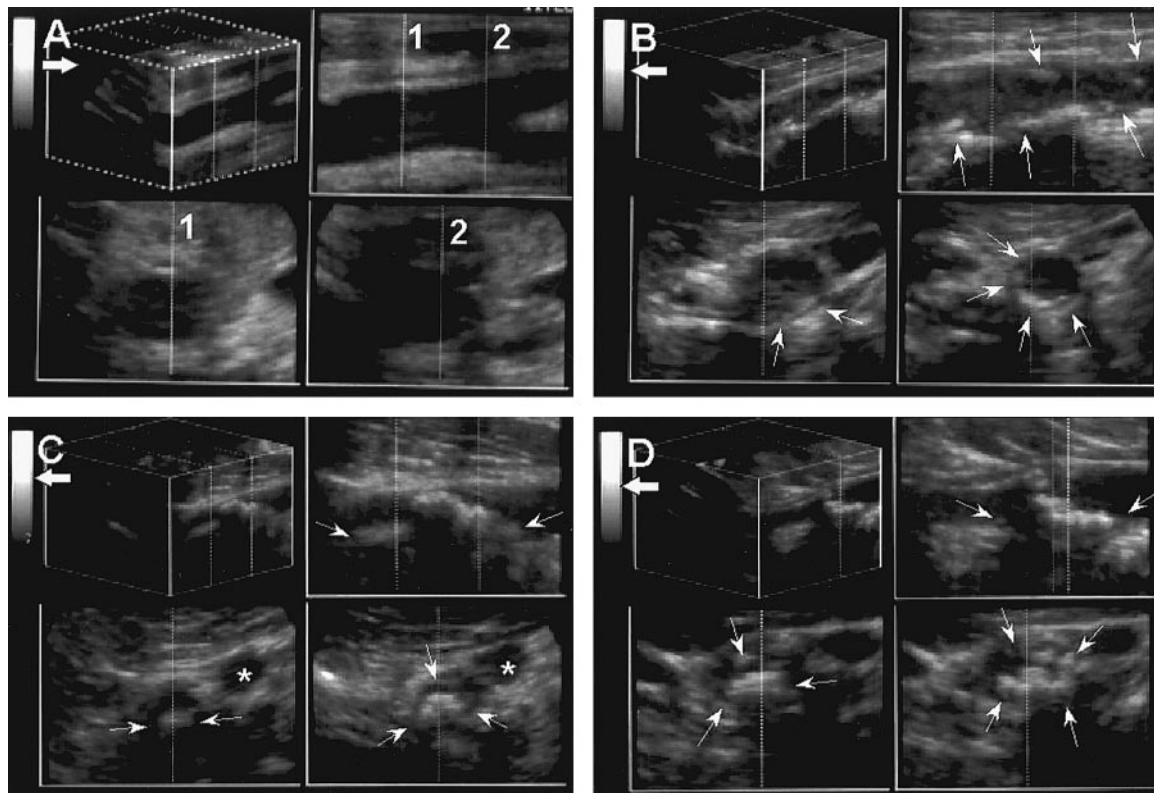
Figure 7. Images reconstructed from 3-D ultrasound of the carotid arteries in different patients, labeled A, B, C, and D. The thick arrow in each panel under the capital letter indicates the direction of carotid artery from proximal to distal. Four images are shown in each panel as they appear on the screen of the 3-D ultrasound unit. The upper left image shows the orientation of the volumetric data set in a cube. A cross-sectional cutting plane of the carotid artery can be reconstructed through guidance from a spatial coordinate system (upper right image). At the same time, 2 other cutting planes perpendicular to the first are displayed automatically, and their positions are indicated by 2 vertical lines (1 and 2). Panel A shows 3-D reconstruction of a carotid artery after endarterectomy. Panels B, C, and D are examples of multiple plaques with different shapes and distribution (thin arrows). The longitudinal extent of the plaques are shown in the upper right images; the lower images display their circumferential involvement of the vessel and the cross-sectional view of the free carotid lumen as well as the shape of the plaques.

of the patient by reducing the examination time and probe manipulation. A 3-D data set can be collected within 2 seconds, with the probe held in a fixed position. Close examination of the carotid artery can be achieved off-line, and images of the carotid artery can be reconstructed in unrestricted directions from the 3-D data set. Third, it provides volumetric information of not only the free lumen of the carotid artery but also the plaques, the vessel wall, and the adjacent tissue and structures, such as the jugular vein. Information of the shape and distribution of plaques and the degree of calcification may be helpful in clinical management of the patients, such as selection of appropriate interventional methods. And last, 3-D ultrasound permits volume quantification of either a plaque or a segment of free lumen or original vessel lumen. The reproducibility of plaque length and volume measurements in this study, both from the same observer and from different observers, was excellent. This may have important clinical implications in serial follow-up studies. For example, it may provide a reliable method for serially observing the progression or regression of a plaque and/or changes in the severity of stenosis in a segment of the carotid artery. It may also provide a reliable method in follow-up studies after interventional procedures, such as carotid endarterectomy or endoluminal stenting, to observe the local vessel change, plaque reformation, or stent dysfunction, such as inadequate expansion or recoil.

Changes of the segmental vessel volume and, therefore, the average cross-sectional area of the original carotid artery (ignoring the plaques) increased after endarterectomy in patients with patches used on closing of the artery, as can be expected. In patients without application of patches, changes in segmental vessel volumes after surgery were less significant and varied from decrement to increment. This is an interesting observation, although the answer to it is not clear. We believe that the change in segmental vessel volume of the carotid artery after surgery is multifactor dependent. On one hand, the suture might decrease the size of the vessel, resulting in decrease of segmental vessel volume and cross-sectional area. On the other hand, removal of the intima-media complex and the plaque (especially the calcified ones) might increase the distensibility and decrease the recoil force of the involved segment of the vessel, resulting in increase of both segmental volume and cross-sectional area. Better understanding of the impact of endarterectomy on the carotid artery requires further investigation with a larger number of patients.

Limitations of the Study

Our study had several limitations. First, carotid angiography was used as the reference method for quantitation of carotid stenosis. However, it has its own potential limitations in the accuracy of estimating a 3-D stenotic lesion by using a 2-D projection of the

lumen silhouette and by assuming the original lumen size of the vessel at the diseased site. Therefore, although in this study the severity of carotid stenosis measured by 3-D ultrasound using the area method and the diameter method correlated well with the results from carotid angiography, care must be taken when interpreting the results. Second, some problems of the 2-D ultrasound could not be overcome by 3-D reconstruction. For instance, image quality of 2-D ultrasound could not be improved by 3-D reconstruction. On the contrary, interpolation of the spaces between the original 2-D images further decreases the image resolution. Ultrasound artifacts in 2-D images will remain in the 3-D data set, which also affect the reconstructed images. Finally, the number of patients (n=14) examined in this study was small, although the number of vessels we studied (n=40) was considerable. The measurement of plaque volumes could not be validated in this study. Instead, we tested the intraobserver and interobserver variabilities, and the results proved this method to be highly reproducible. In addition, the plaques we observed in this study had various sizes, shapes, and echogenicity. However, the number of lesions was not great enough to divide them into subgroups. Therefore, the accuracy of measurement affected by the tortuosity of the free vessel lumen and by the morphology of the plaques was not examined. Further investigation in a larger population with a wider range of carotid abnormalities is necessary to validate the results from this study.

Conclusions

3-D ultrasound of the carotid arteries can be used to detect and quantify significant and severe carotid stenosis. Its potential in volumetric measurements indicates important clinical implications. Quantification of plaque and vessel volume allows serial follow-up studies of the progression or regression of stenotic lesions and evaluation of interventional procedures.

References

1. European Carotid Surgery Trialists' Collaborative Group. MRC European Carotid Surgery Trial: interim results for symptomatic patients with severe (70–99%) or with mild (0–29%) carotid stenosis. *Lancet*. 1991; 337:1235–1243.
2. Eliasziw M, Smith RF, Singh N, Holdsworth DW, Fox AJ, Barnett HJM, for the North American Symptomatic Carotid Endarterectomy Trial (NASCET) Group. Further comments on the measurement of carotid stenosis from angiograms. *Stroke*. 1994;25:2445–2449.
3. Rothwell PM, Gibson RJ, Slattery J, Sellar RJ, Warlow CP. Equivalence of measurements of carotid stenosis: a comparison of three methods on 1001 angiograms: European Carotid Surgery Trialists' Collaborative Group. *Stroke*. 1994;25:2435–2439.
4. Rothwell PM, Gibson RJ, Slattery J, Warlow CP. Prognostic value and reproducibility of measurements of carotid stenosis. A comparison of three methods on 1001 angiograms: European Carotid Surgery Trialists' Collaborative Group. *Stroke*. 1994;25:2440–2444.
5. Streifler JY, Eliasziw M, Fox AJ, Benavente OR, Hachinski VC, Ferguson GG, Barnett HJ, for the North American Symptomatic Carotid Endarterectomy Trial. Angiographic detection of carotid plaque ulceration: comparison with surgical observations in a multicenter study. *Stroke*. 1994;25:1130–1132.
6. Gagne PJ, Matchett J, MacFarland D, Hauer-Jensen M, Barone GW, Eidt JF, Barnes RW. Can the NASCET technique for measuring carotid stenosis be reliably applied outside the trial? *J Vasc Surg*. 1996;24:449–455.
7. Zhu CZ, Norris JW. Complications of carotid angiography. *J Neurol Neurosurg Psychiatry*. 1991;54:758–759.
8. Gerraty RP, Bowser DN, Infeld B, Mitchell PJ, Davis SM. Microemboli during carotid angiography: association with stroke risk factors or subsequent magnetic resonance imaging changes? *Stroke*. 1996;27:1543–1547.
9. McFarland HR, Pinkerton JA Jr. Comparison of non-invasive carotid tests with angiography in assessing carotid stenosis. *Mo Med*. 1987;84:653–655.
10. Mittl RL Jr, Broderick M, Carpenter JP, Goldberg HI, Listerud J, Mishkin MM, Berkowitz HD, Atlas SW. Blinded-reader comparison of magnetic resonance angiography and duplex ultrasonography for carotid artery bifurcation stenosis. *Stroke*. 1994;25:4–10.
11. Boyle MJ, Wolinski AP, Grimley RP. Accuracy of duplex versus angiography in patients undergoing carotid surgery. *J R Soc Med*. 1995; 88:20–23.
12. Hansen F, Bergqvist D, Lindblad B, Lindh M, Matzsch T, Lanne T. Accuracy of duplex sonography before carotid endarterectomy: a comparison with angiography. *Eur J Vasc Endovasc Surg*. 1996;12:331–336.
13. Prestigiacomo CJ, Connoly ES Jr, Quest DO. Use of carotid ultrasound as a preoperative assessment of extracranial carotid artery blood flow and vascular anatomy. *Nerosurg Clin N Am*. 1996;7:577–587.
14. Cartier R, Cartier P, Fontaine A. Carotid endarterectomy without angiography: the reliability of Doppler ultrasonography and duplex scanning in preoperative assessment. *Can J Surg*. 1993;36:411–416.
15. Dawson DL, Zierler RE, Strandness DE Jr, Clowes AW, Kohler TR. The role of duplex scanning and arteriography before carotid endarterectomy: a prospective study. *J Vasc Surg*. 1993;18:673–680.
16. McKittrick JE, Cisek PL, Pojunas KW, Blum GM, Ortgiesen P, Lim RA. Are both color-flow duplex scanning and cerebral arteriography required prior to carotid endarterectomy? *Ann Vasc Surg*. 1993;7:311–316.
17. Rubinstein D. MR imaging and the evaluation of extracranial carotid stenosis. *AJR Am J Roentgenol*. 1994;163:1213–1214.
18. De Marco JK, Nesbit GM, Wesbey GE, Richardson D. Prospective evaluation of extracranial carotid stenosis: MR angiography with maximum-intensity projections and multiplanar reformation compared with conventional angiography. *AJR Am J Roentgenol*. 1994;163:1205–1212.
19. Furuya Y, Isoda H, Hasegawa S, Takahashi M, Kaneko M, Uemura K. Magnetic resonance angiography of extracranial carotid and vertebral arteries, including their origins: comparison with digital subtraction angiography. *Neuroradiology*. 1992;35:42–45.
20. Dillon EH, van Leeuwen MS, Arancha Fernandez M, Eikelboom BC, Mali WT. Computed tomographic angiography for carotid imaging. *Lancet*. 1992;340:1286. Letter.
21. Dillon EH, van Leeuwen MS, Arancha Fernandez M, Mali WT, Eikelboom BC. Carotid artery imaging with computed tomography angiography. *J Vasc Surg*. 1993;17:624–625. Letter.
22. Goldenberg M. Computed tomographic evaluation of cervical carotid plaque complications . *Stroke*. 1986;17:779. Letter.
23. Pretorius DH, Nelson TR, Jaffe JS. 3-dimensional sonographic analysis based on color flow Doppler and gray scale image data: a preliminary report. *J Ultrasound Med*. 1992;11:225–232.
24. Rosenfield K, Boffetti P, Kaufman J, Weinstein R, Razvi S, Isner JM. Three-dimensional reconstruction of human carotid arteries from images obtained during noninvasive B-mode ultrasound examination. *Am J Cardiol*. 1992;70:379–384.
25. Tarjan Z, Pozzi Mucelli F, Frezza F, Pozzi Mucelli R. Three-dimensional reconstruction of carotid bifurcation from CT images: evaluation of different rendering methods. *Eur Radiol*. 1996;6:326–333.
26. Wilkerson DK, Keller I, Mezrich R, Schroder WB, Sebok D, Gronlund-Jacobs J, Conway R, Zatina MA. The comparative evaluation of three-dimensional magnetic resonance for carotid artery disease. *J Vasc Surg*. 1991;14:803–809.
27. van Alphen HA, Polman CH. Carotid endarterectomy: how does it work? A clinical and angiographic evaluation. *Stroke*. 1986;17:1251–1253.
28. Thompson JE, Talkington CM. Carotid endarterectomy. *Adv Surg*. 1993; 26:99–131.
29. Steiger HJ. Carotid endarterectomy: when to do it, how to do it? *Acta Neurochir (Wien)*. 1995;137:121–127.
30. Hankey GJ, Warlow CP, Sellar RJ. Cerebral angiographic risk in patients with mild cerebrovascular disease. *Stroke*. 1990;21:209–222.
31. Davies KN, Humphrey PR. Complications of cerebral angiography in patients with symptomatic carotid territory ischaemia screened by carotid ultrasound. *J Neurol Neurosurg Psychiatry*. 1993;56:967–972.
32. Williams MA, Nicoliades AN. Predicting the normal dimensions of the internal and external carotid arteries from the diameter of the common carotid. *Eur J Vasc Surg*. 1987;1:91–96.
33. Karnik R, Ammerer HP, Winkler WB, Valentin A, Slany J. Initial experience with intravascular ultrasound imaging during carotid endarterectomy. *Stroke*. 1994;25:35–39.
34. Rankin RN. Fenster A. Downey DB. Munk PL. Levin MF. Vellet AD. Three-dimensional sonographic reconstruction: techniques and diagnostic applications. *AJR Am J Roentgenol*. 1993;161:695–702.