

Examination of the Extracranial Carotid Bifurcation by Thin-Section Dynamic CT: Direct Visualization of Intimal Atheroma in Man (Part 1)

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Because carotid angiography has been shown to have limitations in the detection of intimal disease at the bifurcation, a new method of examination of the extracranial carotid artery has been developed using thin-section dynamic computed tomographic (CT) scanning. Carotid atheroma and thrombi can be imaged directly on these sections. The intimal lesions are uniformly hypodense with respect to the carotid arterial wall. Radiologic-pathologic correlation studies using human carotid arteries in a neck phantom confirm that these hypodense lesions are atheromas or thrombi. There is good correlation between CT cross-sectional images and cross-sectional postmortem artery sections. While a number of new computer-based methods of reformation of the carotid artery have been developed, consecutive thin slices through the carotid bifurcation display the pathologic lesions satisfactorily.

Carotid angiography has been the method of choice for the detection of extracranial carotid artery atherosclerotic disease for many years. However, as Edwards et al. [1] and Croft et al. [2] have pointed out, angiography has marked limitations. Forty percent of surgically confirmed carotid artery lesions were missed on pre-surgical angiograms in patients with lateralized transient ischemic attacks (TIAs). Digital angiography could not exceed the sensitivity of carotid angiography because the resolution is inferior, and patient motion is another problem. Carotid phonoangiography, oculoplethysmography, and Doppler flow analysis with real-time sonographic imaging of the carotid bifurcation all have limitations [2-8]. Because of these limitations we have looked to computed tomography (CT) [9-14], with its inherent capacity to distinguish between tissues of only slightly differing electron density, to image carotid atheroma directly. We had two main objectives: (1) to demonstrate carotid atheroma on CT sections of the neck in carotid artery specimens and clinically in humans and (2) to investigate several new methods of display for the carotid cross-sectional images. A detailed evaluation of the clinical use of CT in patients with extracranial atheromatous disease is the subject of part 2 of this investigation [13].

Materials, Subjects, and Methods

Carotid Specimen Studies

Three carotid arteries were removed from human subjects at postmortem examination. One carotid artery specimen was relatively normal; two showed extensive intimal atheroma and calcification in the wall. The carotid artery was sealed after being filled with methylglucamine diatrizoate 29% diluted 4:1 with water. The carotid arteries were individually suspended in a 20 cm water phantom. Sequential 1.5 mm CT slices were made through the length of the arteries. After scanning, the carotid arteries were filled with barium gel and radiographed. They were then cut in cross section and compared with CT slices at the same level (fig. 1).

Received February 9, 1983; accepted after revision February 17, 1984.

This work was supported by National Institutes of Health grant 1 R01 NS/HL 16759-01.

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AJNR 5:355-359, July/August 1984
 0195-6108/84/0504-0355 \$2.00
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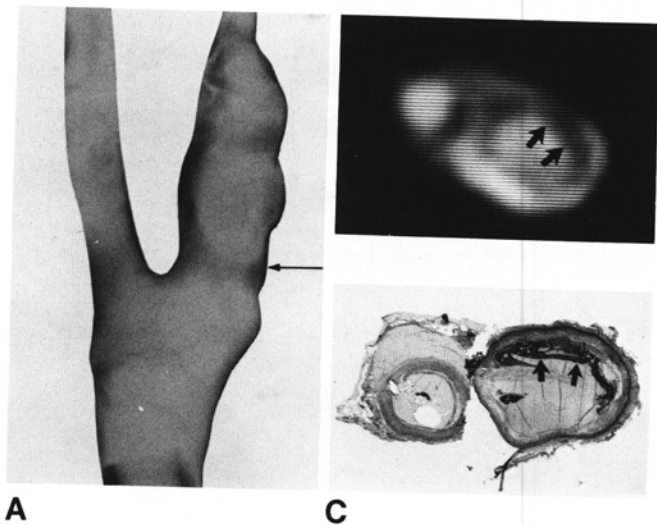


Fig. 1.—Radiologic-CT-pathologic correlation study of human carotid artery. **A**, Specimen radiograph of human carotid artery postmortem from 60-year-old man. Barium gel injection. Subtle transverse band of increased density at origin of internal carotid artery (arrow). **B**, CT scan of same carotid artery in 25 cm water phantom. Hypodense area parallel to internal carotid wall (arrows) is extensive organizing thrombus, which is hypodense with respect to arterial wall. **C**, Pathologic macrosection of same carotid artery. Organizing thrombus (arrows) adjacent to internal carotid artery wall closely corresponds to hypodense area in **B**. Microscopic analysis shows red blood cells trapped in fissures within clot, confirming this as recent, organizing thrombus adherent to carotid intima.

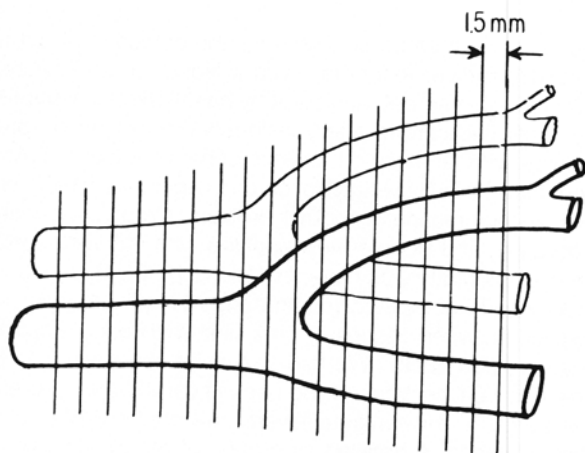


Fig. 2.—CT scanning of extracranial carotid artery by thin-section CT. Using GE 8800 scanner, 24 to 36 1.5-mm-thick scans with 1.5 mm table increments cover up to 5.4 cm of carotid artery and bifurcation between C6 and C3. Only 17 slices represent scanning process here. With GE 9800 scanner 10 3-mm-thick scans with table increment of 3 mm obtained.

Clinical Studies

Eleven patients suspected of having cerebral vascular disease were examined. The main objective was to develop a reproducible technique for the detection of atheromatous disease in the extracranial carotid arteries. To this end, several CT and injection techniques (figs. 2 and 3) were used, and later, several display techniques were developed to improve on this new technique (figs. 4 and 5).

Contrast injection and CT scanning technique. The patient lies supine on the scanner with his forehead lightly taped; he is urged to hold his breath for each scan and not to swallow. Immediately after rapid infusion of 150 ml of Renografin 60, the scan sequence is begun. At this point, a bottle of Reno-M-Dip 30 (methylglucamine diatrizoate, Squibb) is infused at 50–60 drops/min; rapid scanning of the neck requires about 5 min with the GE 9800 and 8 min with the GE 8800; the infusion is discontinued when the last scan is completed. The average study on the GE 9800 requires about 50 g of iodine; the average study on the GE 8800 requires about 60–70 g of iodine.

Twenty-four to 36 1.5 mm contiguous slices were taken along the course of the common carotid artery, the bifurcation, and the internal and external carotid arteries with the GE 8800. This is done by scanning the neck from C6 to C3. Each GE 8800 scan requires 9.6 sec at 160 mA using prospective soft-tissue target software reconstruction (General Electric software program). More recently we have been using the GE 9800; 12 3 mm CT slices were obtained using the GE 9800 with a 3 mm table increment between scans. Each GE 9800 scan requires 2 sec at 300 mA. The kilovoltage was 120 with each machine. CT scans illustrating a normal carotid artery are seen in figure 3.

Display techniques:

1. Single CT slices: Single 1.5 mm slices were displayed in sequence using the General Electric multiformat camera.
2. GEDIS ± ARRANGE software program: Using the General Electric ARRANGE software program a number of reformations paralleling the long axis of the artery were made [15].
3. Slice edge presentation with 3-D hiding. Utilizing edge detection and boundary tracking algorithms, a new computer graphics 3-D display was developed [16]. This computer technique provides multiple 2-D reformation images, each at 15° tangent with respect to the image next to it (fig. 4).
4. A computer-generated reformation that uses triangular tiles to create a surface "skin" over the edges of carotid artery on each of the slices has been developed [17] (fig. 5). A 3-D contour of the bifurcation is suggested by use of highlights and shadows.
5. A new 3-D display system using the varifocal mirror principle was developed (S. M. P. and H. F.). This display, in which 36 consecutive carotid scans are displayed simultaneously like a stack of coins, is discussed in detail elsewhere [12].

Results

Carotid Specimen Studies

CT sections of human carotid arteries correspond closely to cross sections of the same artery prepared as macrosections for pathology. In one of these specimens there was a recent, organizing thrombus closely adherent to the internal carotid intima. Erythrocytes trapped in the thrombus confirmed its recent formation. The thrombus could not be detected readily in the barium gelatin injection specimen resembling a carotid arteriogram (fig. 1A). The thrombus was easily detected on the CT specimen study (fig. 1B). However, thrombus cannot be differentiated from atheroma in the carotid artery by this technique.

Clinical Studies

Eleven patients (22 carotid arteries) were studied. Certain features are evident on the CT studies. The common carotid artery, carotid bifurcation, and internal carotid artery can be

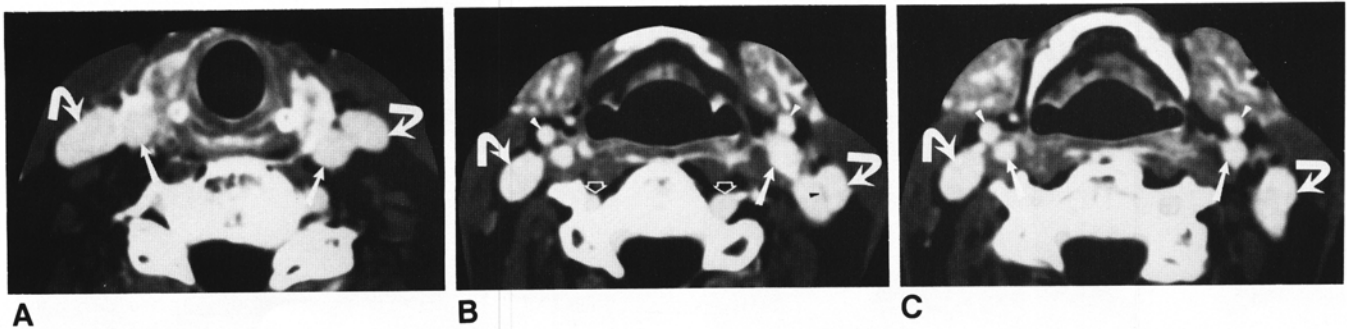


Fig. 3.—Normal carotid arteries. Ten 3 mm CT slices with table increment of 3 mm were completed within 5 min on GE 9800 CT unit. **A**, Common carotid artery. CT section at C6 shows round or oval common carotid artery (straight arrows). Internal jugular vein (curved arrows) lies immediately adjacent and anterolateral, lateral, or posterolateral to carotid artery. **B**, Carotid bifurcation at lower half of C4. Oval configuration of left carotid bifurcation (solid straight arrow). Smaller external carotid is seen anteriorly (white arrowheads). Two

veins have just joined together to form internal jugular vein so it is septated on this scan (black arrowhead). Larger left and smaller right vertebral arteries are demonstrated (open arrows). **C**, Internal and external carotid arteries at upper half of C4. Internal carotid artery (straight arrows) is slightly larger and posteromedial to external carotid (arrowheads). At this level, cephalad to bifurcation, arteries usually lie at some distance from internal jugular veins (curved arrows).

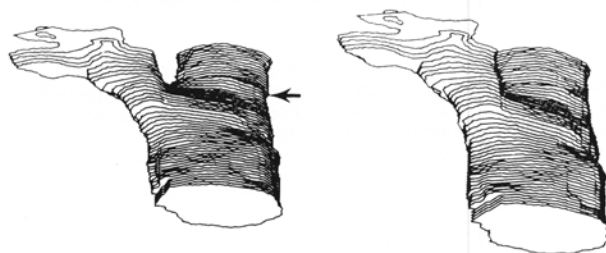


Fig. 4.—Computer reconstructions of carotid bifurcation by edge-detection and boundary-search program are 15° apart. Fairly normal-appearing carotid bifurcation showing proximal internal and external carotid arteries. Slight motion artifact (arrow).

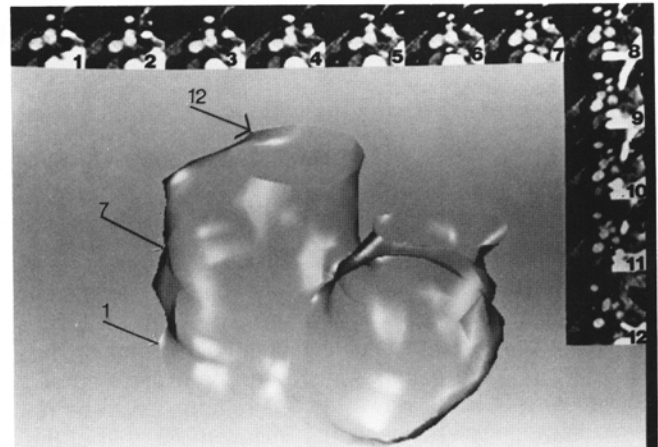


Fig. 5.—3-D reformation on 2-D display CRT by shaded graphics (photograph of CRT monitor). Left carotid artery bifurcation is reformation of 14 1.5 mm CT slices through neck. Nos. 1, 7, and 12 correspond to levels of CT slices beginning in left top corner of CRT display (no. 1) continuing to upper right corner (no. 7); no. 12 is lowest of five slices. No. 12 arrow indicates internal carotid artery distal to bifurcation. This shaded graphic image does not show actual gray scale; it mainly serves as frame of reference for individual slices on perimeter, locating them in overall carotid bifurcation reformation.

seen easily and clearly with this technique. The carotid artery, while immediately adjacent to the jugular vein in the carotid sheath, can always be separated from the vein. The two vessels form two discrete circles immediately contiguous with one another. The carotid artery always lies anteromedially with respect to the larger jugular vein. Both are filled with dense contrast material. The arterial wall is hypodense when compared with the high density of contrast material in the lumina of the jugular vein and carotid arteries. The wall of the jugular vein is too thin to be visualized (figs. 3 and 6). In areas of the carotid artery not covered by the vein, the wall is readily distinguished from the fat (low density) that surrounds the artery. While arterial motion might be anticipated that would lead to unsharp arterial images, in fact, the carotid images are quite sharp (figs. 3 and 6). Obviously the images acquired over the 9.6 sec scanning period are the result of averaging of arterial variations with each heartbeat. Observations in patients with pathologic carotid arteries include direct imaging of carotid clot and intimal atheroma; these pathologic areas are usually hypodense with respect to the arterial wall and the iodine-filled lumen [13] (fig. 6). They cannot be differentiated by this technique. These hypodense filling defects were seen in seven of eight TIA patients; in none of the patients were the defects hyperdense [15]. Calcification, often exten-

sive, is noted in the arterial wall [18]. Calcification is not usually seen in the atheroma or in the organizing clot within the lumen (fig. 6).

Display techniques:

1. Single serial CT sections through the carotid artery can be displayed nicely on GE multifram camera 14 × 17 inch (36 × 43 cm) films. However, for those who are not familiar with the technique, it is helpful to have some type of reconstruction that displays the artery along its long axis so that individual slices can be localized.

2. The GEDIS-ARRANGE system provides quite good paraaxial reformations. These reformations resemble carotid angiograms and therefore are of assistance in viewing the multiple cross-sectional images of the arteries. However,

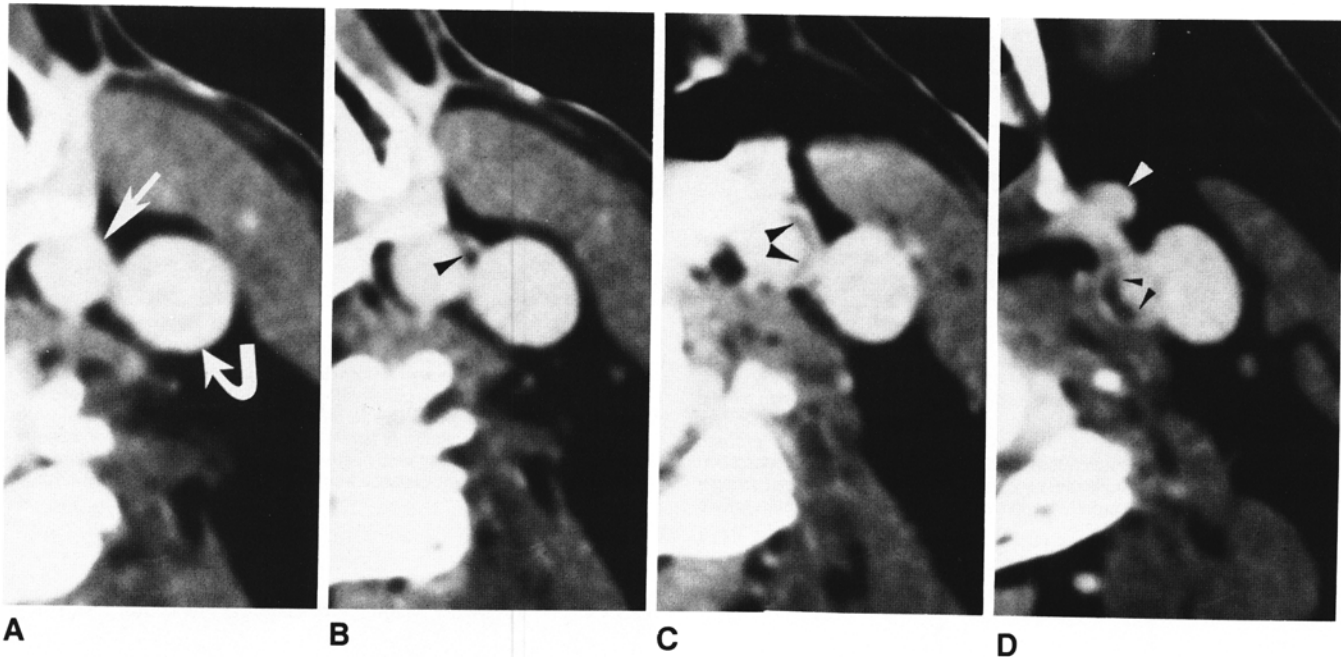


Fig. 6.—Direct imaging of carotid artery atheroma by CT. These four images from series of 12, using 3 mm slice thickness, 3 mm table increment, and 8 sec interscan time, were completed in less than 5 min. **A**, Left common carotid (straight arrow) artery at lower half of C6. Large internal jugular vein (curved arrow). **B**, Common carotid artery at upper half of C6, just proximal to carotid

bifurcation. Hypodense filling defect on lateral wall represents discrete atheroma (arrowhead). **C**, Proximal carotid bifurcation at C5. Atheroma (arrowheads) follows contour of intima laterally. **D**, Internal and external carotid (white arrowhead) arteries at distal bifurcation. Atheroma adjacent to intima all 360° of artery (black arrowheads).

there are problems because of the difficulty in picking a plane that passes through a tortuous common carotid and internal carotid artery.

3. The slice-edge presentation method of reformation (fig. 4) provides a good reference image for the multiple carotid transverse sections. It allows the 3-D reformation to be re-viewed from multiple tangents. Its limitation, like that of the shaded graphics display that follows, is that it is represented in black and white only; there is no gray scale.

4. The shaded graphics method [16] offers a 3-D-type image on a 2-D CRT display in which the computer creates triangular tiles that cover the adjacent slice edges with a "skin." In addition, this technique makes the carotid artery appear three-dimensional; this is done by the use of a constant light source from behind the observer's head that creates highlights and "shadows" on the carotid bifurcation. These give the impression of a striking depth perception (fig. 5).

5. Finally, the varifocal mirror system was completed [12]. This imaging technique provides an excellent 3-D image with much better depth clues than is possible with stereo imaging. The observer looks into the mirror, which is directed toward the face of the CRT upon which 30 to 50 CT slices are recorded in less than $\frac{1}{30}$ of a sec. The carotid artery image may be rotated or turned end-over-end by a joystick. In addition, one can see the other side of the image by simply moving the head with respect to the mirror. However, it is not possible to make a good hard copy of this 3-D image, an important disadvantage.

Discussion

Thin-section CT examination of the carotid artery is the first study to image carotid atheroma or clot directly. The study can be done in the dead time between the unenhanced and enhanced CT scan. The actual picture-taking requires less than 12 min. No new radiologic equipment is required. Direct CT visualization of the carotid artery cross section effectively displays the atheroma or clot directly as well as the size of the lumen and the state of the rest of the arterial wall. These CT images of the carotid arteries appear to compare very favorably with the few postmortem transverse sections that have been done. In the past, angiography has been the "gold standard" for the diagnosis of carotid atheroma and thrombus. However, the diagnosis has always been inferred from indirect evidence—the edge distortion of the intraluminal contrast column. Digital angiography has the same limitation with less resolution.

With the long CT exposures, one would expect significant vascular pulsation that, in turn, would degrade the transverse images of the artery. However, the CT images are quite sharp.

We have tried to develop this technique to overcome two potential causes of the high false-negative rate with carotid angiography [1]. The transverse images overcome the need for multiple radiographic views of the carotid artery for the detection of edge abnormalities; further, the CT transverse images appear to be superior for the evaluation of carotid atheroma, which is hidden by the density of the contrast column.

In conclusion, thin-section CT examination of the extracranial carotid arteries can demonstrate intimal atheroma and thrombi. CT findings in eight consecutive patients with TIAs are reported in part 2 [13].

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