Intravascular Ultrasound Evaluation of the Effect of Rotational Atherectomy in Obstructive Atherosclerotic Coronary Artery Disease

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Background. High-speed rotational atherectomy uses a diamond-coated, elliptical burr to abrade occlusive atherosclerosis, especially noncompliant calcified plaque.

Methods and Results. Intravascular ultrasound (IVUS) was used to analyze 28 patients after atherectomy. Arteries treated and imaged were left main (three), left anterior descending (12), left circumflex (five), right coronary (seven), and saphenous vein graft (one). Twenty patients had adjunct balloon angioplasty. Twenty-two (79%) target lesions were calcified; the intimal arc of calcium was 160±126° (range, 0–360°). After atherectomy, the intima-lumen interface was unusually distinct and circular. The lumen was larger than the largest burr used for both stand-alone (1.19±0.19-fold the largest burr size) and adjunct balloon procedures (1.30±0.15-fold the largest burr). Three-dimensional reconstruction of the ultrasound images showed a smooth lumen, especially in calcified plaque. Deviations from cylindrical geometry occurred only in areas of soft plaque or superficial tissue disruption of calcified plaque. Five patients were studied before and after rotational atherectomy. IVUS showed an increase in lumen size, a decrease in plaque-plus-media area and in arc of target lesion calcification, and no change in target lesion external elastic membrane cross-sectional area.

Conclusions. Rotational atherectomy causes atheroablalation with only moderate evidence of barotrauma in heavily calcified arteries, even after adjunct balloon angioplasty. The lumen is cylindrical, especially in areas of calcified plaque, and somewhat larger than the largest burr tip used. (Circulation 1992;86:1383–1393)

KEY WORDS • angioplasty • calcium • atherectomy • intravascular ultrasound

Rotational atherectomy uses a high-speed, rotating, diamond-coated, elliptical burr to abrade occlusive atherosclerotic material to restore lumen patency.1 In vitro studies using cadaver peripheral arteries have suggested that this technique selectively removes noncompliant plaque material, especially calcium.2-4 However, there has been little study of the effects of high-speed rotational atherectomy on human coronary atherosclerosis in vivo. The purpose of this study was to use intravascular ultrasound (IVUS) to examine the effects of high-speed rotational atherectomy on human atherosclerotic coronary arteries in vivo.

Methods

Twenty-eight patients underwent successful rotational atherectomy (Rotablator, Heart Technology, Bellevue, Wash.) followed by IVUS imaging. There were 21 men and seven women with a mean age of 64±7 years. Arteries treated and imaged were left main (three), left anterior descending (12), circumflex (five), right coronary (seven), and saphenous vein bypass graft (one).

Rotational Atherectomy Procedure

A standard 9F guiding catheter was placed into the ostium of the coronary artery or vein graft. The dedicated 0.009-in. 300-cm stainless-steel guidewire was advanced through the narrowing and into the distal part of the coronary artery. Initially, a 1.25-, 1.50-, or (for the vein graft) 2.0-mm abrading burr tip was advanced over the guidewire and placed just proximal to the stenosis. The system was activated, and when adequate rotational speed (>175,000 rpm) was achieved, the burr tip was advanced slowly in a gentle “pecking” motion. After crossing the lesion, the burr tip was withdrawn, and subsequent advancement sequences were performed until tactile and visual resistance disappeared. The initial burr was then exchanged for a larger one, and the procedure was repeated; the largest burr tip was selected to be approximately 70–80% the size of the reference vessel lumen. The largest burr tip used ranged from 1.75 to 2.50 mm (mode, 2.0 mm). Two or three burrs were used in every patient. Adjunct balloon angioplasty was performed if coronary arteriography showed vasospasm, hazziness, irregularity, or a residual stenosis >30%. Adjunct balloon angioplasty was performed in 20 patients (71%). The balloon size

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FIGURE 1. Intravascular ultrasound image shows how careful axial movement of the transducer unmasks adventitia contiguous to calcified plaque. Ten cross-sectional images are shown that are 0.1 mm apart on center. The entire figure represents a section of artery <1 mm in length. The most proximal image is on the right; a calcific deposit obscures the adventitia (four small white arrows). The most distal image is on the left; the contiguous adventitia is unmasked (two large white arrows).

Point-to-point resolution along the ultrasound beam axis was calculated from transducer frequency and wavelength and from the speed of ultrasound transmission in tissue and was 100 μm for the 20-MHz catheter and 80 μm for the 25-MHz catheter. The maximal penetration depth was 8 mm; this also was a function of the composition of the tissue being imaged. Using pulsed-echo techniques, a mirror reflected the ultrasound beam perpendicular to the long axis of the probe. Planar two-dimensional images were formed in real time by motor rotation of the entire ultrasound catheter within its imaging sheath at 1,800 rpm. Five of these patients were studied both before and after atherectomy using

FIGURE 2. Intravascular ultrasound image shows a fissure in a circumferentially calcified plaque after rotational atherectomy and adjunct balloon angioplasty (patient 19). Slow pullback of the catheter localizes the superficial break in calcium (small white arrows) to an axial arterial segment of 0.1 mm. Four cross-sectional images are shown that are 0.05 mm apart on center. The most distal image is on the left.

ranged from 2.5 to 4.0 mm (mean, 3.2±0.5 mm). During the procedure, intracoronary nitroglycerin was given liberally with 200 μg typically given after each passage of the burr, or dilatation of the balloon and intravenous nitroglycerin was infused to maintain systolic blood pressure between 100 and 140 mm Hg.

**IVUS Imaging System**

We used the InterTherapy, Inc. (Santa Ana, Calif.) intravascular ultrasound imaging system with either a 20-MHz transducer-tipped catheter within a 4.9F polyethylene sheath or a 25-MHz transducer-tipped catheter within a 3.9F polyethylene sheath in 26 patients.
the 3.9F catheter and a mechanized pullback device. By using the aorto-ostial junction as a longitudinal reference and by knowing the precise pullback speed (usually 0.5 mm/sec), the same cross-sectional slice of the coronary artery could be imaged reproducibly for comparative studies. Studies done using this motorized pullback device provided source material for many of the illustrations shown.

We used the CVIS (Cardiovascular Imaging Systems Inc., Sunnyvale, Calif.) IVUS system in two patients. The 4.3F catheter incorporates a 30-MHz transducer that has a point-to-point resolution along the ultrasound beam axis of 67 μm and a maximum tissue penetration of approximately 5 mm depending on the tissue type imaged. The transducer is fixed and the angled mirror is rotated to form real-time planar two-dimensional images.

Data were stored on 0.5-in. high-resolution videotape. Quantitative analysis was performed either on-line or off-line. Validation for coronary artery and plaque composition and morphology and measurements of external elastic membrane cross-sectional area (CSA), residual lumen CSA, plaque-plus-media CSA, and plaque composition by IVUS have been reported previously.\(^3\)\(^-\)\(^7\)

All data presented were derived from analysis of IVUS studies performed after intervention was completed (stand-alone rotational atherectomy in seven patients and combined rotational atherectomy—adjunct balloon angioplasty in 21 patients). In addition, five of these patients were studied before intervention. None of these patients were studied before intervention, after rotational atherectomy, and after balloon angioplasty.

Three-dimensional Reconstruction of IVUS Images

We used computerized software developed by Pura, Inc. (Brea, Calif.) and hardware from ImageComm (Santa Clara, Calif.) to perform three-dimensional reconstruction of IVUS images. The software-encoded algorithm used a thresholding approach to render the three-dimensional image. The hardware can digitize up to 6 frames/sec. Accurate three-dimensional modeling was possible in 11 patients studied using the InterTherapy system because of the use of the mechanized pullback device described above. The pullback device withdraws the InterTherapy imaging catheter at a rate of 0.5 mm/sec. In analog format, each millimeter of artery is represented by 60 equally spaced image slices. After sampling and digitalizing, each millimeter of artery is represented by approximately 12 image slices. A maximum of 230 digitized images can reconstruct a segment of artery 19 mm long. A single processing element performs all computation. Regions of interest were set to include arterial structures between the adventitia and intima and to exclude the imaging sheath. The threshold was set just low enough to exclude lumen blood echoes.

Angiographic Criteria

Angiograms were analyzed by an independent core angiographic laboratory. With quantitative coronary arteriography (Artrek, Ann Arbor, Mich.) lesion length, minimum lumen diameter, and percent diameter stenosis before and after balloon angioplasty were measured in orthogonal projections. Lesion morphology was graded according to American College of Cardiology/American Heart Association criteria (ACC/AHA).\(^8\) Calcification was evaluated on fluoroscopy. The presence or absence of dissections was noted by contrast angiography and graded according to National Heart, Lung, and Blood Institute (NHLBI) criteria.\(^9\) A dissection was considered extensive (NHLBI type C) if it protruded outside the lumen of the artery and persisted after passage of contrast media.

Quantitative and Qualitative Ultrasound

With computer planimetry, CSAs were measured at the atherectomy site and at a proximal reference site. The CSAs confined within the external elastic membrane and of the residual lumen at the smallest residual lumen were measured. The plaque-plus-media CSA was calculated by subtracting the residual lumen CSA from the external elastic membrane CSA. The smallest and

![Figure 3](http://circ.ahajournals.org/lookup/suppl/doi:10.1161/01.CIR.78.7.1385/-/DC1/FIG3.jpg)

**Figure 3.** Intravascular ultrasound image shows a dissection in a circumferentially calcified plaque after rotational atherectomy and adjunct balloon angioplasty (patient 19). Slow pullback of the catheter localizes the break in calcium (small white arrows) to a 1.0-mm-long arterial segment. The circumferential extension of the dissection is 40°. Eight cross-sectional images are shown that are 0.2 mm apart on center. The most distal image is on the left.
### Table 1. Twenty-eight Patients Imaged After Rotational Atherectomy

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EEM, external elastic membrane; CSA, cross-sectional area; D, diameter; Max, maximal; Min, minimal; MLD, minimal lumen diameter; LCx, left circumflex; LAD, left anterior descending coronary artery; RCA, right coronary artery; SVG, saphenous vein graft.

*Could not measure because dense intimal calcification caused acoustic shadowing of deeper tissue planes.
†Could not measure because lesion site was ostial.

Largest lumen diameters (major and minor axes) also were measured.

Lesion calcification causes shadowing of deeper tissue planes (including the adventitia), potentially making measurement of the external elastic membrane difficult. However, two approaches circumvented this problem. First, because the coronary artery is tubular and its cross section is circular, circumferential extrapolation of the external elastic membrane is possible as long as each calcific deposit does not shadow more than approximately 60° of the adventitial circumference. Second, real-time axial movement of the transducer just proximal or distal to each calcific deposit unmask and fills in contiguous parts of the adventitia otherwise shadowed by that calcific deposit (Figure 1). Unmasking and filling-in of contiguous portions of the adventitia were facilitated by use of the motorized pullback device, which moves the transducer in small increments. Transducer movement to unmask the adventitia permitted measurement of external elastic membrane CSA in patients with short extensive arcs of calcium of up to 300° in one instance. These two approaches allowed measurement of external elastic membrane CSA in all except eight patients.

Arterial expansion after rotational atherectomy was defined as an external elastic membrane CSA at the atherectomy site that was larger than the external elastic membrane CSA at a proximal reference site.

The intimal circumference of lesion calcification (arc of calcium in degrees) was measured using a protractor centered on the imaging sheath. Calcified plaques had bright echoes (bright than the reference adventitia) that emanated from the plaque with acoustic shadowing.5-7,8,10 Because of acoustic shadowing, the thickness or CSA of a calcified deposit cannot be measured.

Dense fibrous tissue is as bright or brighter than the reference adventitia but lacks acoustic shadowing. Soft plaque (containing intimal hyperplasia, lipid, or loose connective tissue) is less bright than the reference adventitia.

A fissure was defined as an abrupt, focal, or superficial break in the linear continuity of the plaque or
normal intima without extension (Figure 2). A dissection was defined as an abrupt break in the linear continuity of the plaque or normal intima that extended in axial, radial, or circumferential directions (Figure 3). An extensive dissection contained two or more dissection planes with at least one extending to the adventitia. The number of fissures or dissections at each atherectomy site was recorded. The extent of dissection in all three directions can be appreciated only in real-time study. A dissection typically bridges radial tissue planes or extends axially. If a large echolucent zone potentially representing media could not be separated acoustically from a dissection, then a dissection was not counted. Similarly, a sharp echolucent zone at the junction of calcified and noncalcified intima extending only radially and potentially representing dropout was not counted as a dissection. This limited the overestimation of arterial dissections.

In our laboratory, the intraobserver variability in measurement of external elastic membrane and lumen diameter and CSAs is ±4% (p = NS); the interobserver variability is ±8% (p = NS). The intraobserver variability in measurement of the intimal arc of calcium is ±5° (p = NS); the interobserver variability is ±15° (p = NS). Determination of plaque composition (calcified versus dense fibrous versus soft), number of dissections, and number of fissures were arrived at by consensus of two or more investigators. Disagreement on the number of dissections was ±1 dissection plane per lesion (p = NS). Disagreement on the number of fissures was ±1 fissure per lesion studied (p = NS).

Statistical Analysis
ANOVA, paired or unpaired student’s t test, χ² analysis, and Fisher’s exact test were used as appropriate.

Results

Angiographic Findings

By fluoroscopy and IVUS, the same 22 sites (79%) were calcified. The prerotational atherectomy percent diameter stenosis was 73 ± 9% (range, 59–87%). The prerotational atherectomy minimal lumen diameter was 0.7 ± 0.3 mm (range, 0.3–1.6 mm). The final postprocedural percent diameter stenosis was 24 ± 9% (range, 8–40%). The final minimal lumen diameter was 1.9 ± 0.4 mm (range, 1.2–3.0 mm). The residual angiographic percent diameter stenosis did not vary with the amount of calcium present by fluoroscopy or IVUS. Mean lesion length was 9.5 ± 6.4 mm (range, 3.5–27 mm). ACC/AHA lesion morphology was B for 12 sites and C for 16 sites. There were five angiographic dissections; none were extensive.

FIGURE 4.  Panel A: Prerotational atherectomy angiogram (left anterior oblique projection, cranial angulation) showing a severe narrowing (arrow) in the left anterior descending artery from patient 4. Panel B: Burr (arrow) in the heavily calcified anterior descending artery. Panel C: Postrotational angiogram showing marked improvement (arrow). Panel D: Intravascular ultrasound image of the rotational atherectomy site. Note the 360° circumferential calcium with a smooth intima-lumen interface. The largest burr used was 2.0 mm. There was no adjunct balloon angioplasty. The residual lumen measured 3.8 x 2.9 mm.
Analysis of IVUS After Rotational Atherectomy

Of the 28 atherectomy sites, 22 were calcified and six were noncalcified (Table 1). Five of the noncalcified sites contained soft plaque; the saphenous vein graft stenosis contained dense fibrous tissue. The intimal arc of calcium averaged 160±126° (range, 0–360°). Sixteen of 22 patients (73%) with calcified target lesions required adjunct balloon angioplasty, and five of six patients (83%) with noncalcified target lesions required adjunct balloon angioplasty.

After rotational atherectomy, the interface between lumen and calcified plaque appeared unusually sharp, clear, and distinct, more so than is typical for borders of calcified plaque (Figures 4–6). This was also true of the saphenous vein graft after atherectomy and adjunct balloon angioplasty (Figure 7). The cross-sectional appearance of the lumen was circular; the ratio of major to minor axis diameters at the treatment site averaged 1.1±0.1 (range, 1.0–1.3).

After rotational atherectomy (and after adjunct balloon angioplasty when necessary), the target lesion site external elastic membrane CSA measured 14.6±3.0 mm², the residual lumen CSA was 6.9±2.2 mm², the minimum lumen diameter was 2.6±0.4 mm, and the plaque-plus-media CSA was 7.9±2.7 mm². Thus, the residual plaque-plus-media CSA averaged 54% of total arterial CSA. There was no correlation between IVUS and quantitative angiographic measurements of minimum lumen diameter after rotational atherectomy. However, in general, IVUS diameters were 35% larger than angiographic diameters.

In eight patients, dense lesion calcification with marked axial extension precluded measurement of the external elastic membrane CSA at the lesion site. One of these patients had an ostial right coronary artery lesion site with no definable proximal reference site. None of the remaining 20 patients had arterial expansion after rotational atherectomy; this included the six patients with noncalcified target lesions (Figure 8).

When the minimum lumen diameter was divided by the largest burr tip used, the ratio range was 0.93–1.45 (1.19±0.19) for stand-alone rotational atherectomy and 1.02–1.56 (1.30±0.15, p=NS) for atherectomy plus adjunct balloon angioplasty. Thus, there is a trend toward a larger lumen than can be accounted for by the size of the burr alone; this was true regardless of the amount of calcium present and whether adjunct balloon angioplasty was used.

Using IVUS, fissures were observed in nine of 28 lesion sites (32%), and dissections were observed in eight of 28 atherectomy sites (29%). There were 0.4±0.7 dissections per lesion. No dissection was extensive. Six of eight patients with a postprocedural dissection had adjunct balloon angioplasty; two did not. Thus, 12 of 28 patients (43%) had a fissure or dissection. Typically, these dissections and fissures occurred within calcified plaque deposits. IVUS detected dissections in three patients in whom dissections were not seen angiographically. Angiography did not detect any dissections not seen by IVUS.

Analysis of IVUS in Patients Studied Both Before and After Atherectomy

Five patients were studied both before and after rotational atherectomy (Table 2 and Figure 8). In four, complete quantitative measurements were possible.

![Figure 5](image-url)

Figure 5. Panel A: Prerotational atherectomy angiogram (right anterior oblique projection) showing a severe narrowing (arrow) in the left circumflex artery from patient 1. Panel B: Postrotational atherectomy angiogram showing a marked improvement (arrow). Panel C: Diamond-tipped burr (arrow) in the left circumflex. Panel D: Intravascular ultrasound image of the rotational atherectomy site. Note two arcs of calcium (large white arrows) at 5 o'clock and 11 o'clock measuring 90° and 40°, respectively. The residual intima-lumen interface is smooth regardless of whether the residual atherosclerosis is calcified or fibrotic (two small white arrows). The largest burr used was 2.15 mm. The adjunct balloon size was 4.0 mm. The residual lumen measures 2.7×3.5 mm.
Three of these four had adjunct balloon angioplasty. There was a significant increase in lumen area (1.8±1.0 to 6.4±1.8 mm², p=0.01) and a significant decrease in plaque-plus-media CSA (12.6±3.6 to 7.3±2.4 mm², p=0.012). There was a tendency for the arc of calcium to decrease (211±126° to 120±87°, t=2.42) in the four calcified target lesions, but this decrease did not reach statistical significance. The target lesion site external elastic membrane CSA did not increase in any patient.

**Three-dimensional Reconstruction**

Three-dimensional reconstruction of the IVUS images showed a smooth, cylindrical lumen, especially in areas of extensive axial and circumferential calcium. Roughened intimal surfaces were present only in areas of noncalcified plaque or indicated a superficial dissection plane in calcified plaque (Figure 9). The amount of surface calcium present after atherectomy could be evaluated by viewing the artery from without; adventitial dropout (from acoustic shadowing) reflects underlying plaque calcium.

**Discussion**

High-frequency IVUS provides detailed transmural high-quality images of human coronary arteries in vivo. The normal coronary artery architecture and the major components of the atherosclerotic plaque can be studied in vivo in a manner not possible previously. We chose to

**FIGURE 6.** Intravascular ultrasound image shows entire length of the rotational atherectomy site in patient 19. Nine cross-sectional images are shown that are 3 mm apart on center. The most distal image is on the left. There is heavy circumferential and longitudinal calcium, especially at the narrowest residual lumen, which measures 2.3×2.7 mm. The largest burr used was 2.15 mm; the adjunct balloon size was 3.0 mm.

**FIGURE 7.** Panel A: Prerotational atherectomy angiogram of the saphenous vein bypass graft from patient 15; the black arrow shows the long stenosis. This long narrowing was not dilatable on two previous balloon angioplasties at inflation pressures of up to 20 atm. Panel B: Saphenous vein bypass graft after atherectomy; note the marked improvement (arrow). Panel C: Diamond-tipped burr (arrow) in the saphenous vein bypass graft. Panel D: Intravascular ultrasound image after rotational atherectomy and adjunct balloon angioplasty. Note the round lumen with a smooth intima-lumen interface. There is extensive fibrosis but no calcification. The residual lumen measured 3.5×3.4 mm. The largest burr used was 2.5 mm; the adjunct balloon size was 3.5 mm.
use IVUS to evaluate coronary artery morphology in humans in vivo before and/or after successful rotational atherectomy to assess the mechanism of this procedure and its effect on coronary artery architecture.

In previous studies, the acoustical signature of arterial plaque calcium, dense fibrous tissue, and soft plaque has been validated in vitro.5-7 Calcium is identified as bright echoes casting echo-free shadows into deeper tissue zones. A heavily calcified plaque may preclude ultrasound interrogation and quantitative analysis of deeper structures. In this study, 22 arteries were calcified, and six arteries were noncalcified. Calcium occupied up to 360° of the intima circumference. Seven patients had circumferential or near-circumferential target lesion calcification. In eight of our patients, we could not assess deeper arterial structures adequately because of acoustic shadowing. Circumferential extrapolation and transducer movement to unmask these deeper structures made measurement of external elastic membrane CSA possible in most of these calcified arteries.

Cross-sectional quantitative analysis of normal and atherosclerotic coronary arteries also has been validated in vitro.5-7 Significant correlations were found between paired ultrasound and histological measurements. Similarly, in vitro ultrasound studies of atherosclerotic arteries before and after balloon angioplasty have demonstrated dissections that coincided with the histology.12

In vitro experimental studies show that the residual lumen after high-speed rotational atherectomy is smooth, shiny, and polished. The endothelium is denuded, various portions of the atheromatous plaque are ablated, damage to the media is minor, and dissections are not present.2-4 The device preferentially cuts hard and even calcified atherosclerotic plaque; microfissures are created at the contact zone of the burr and hard tissue. The microfissures seen histologically in experimental models of rotational atherectomy are not seen in human coronary arteries in vivo using intravascular ultrasound.

There are several possible explanations. First, these microfissures are too small to be detected by IVUS. Second, the intense acoustical reflection from the lumen-intima interface (especially with calcified intima) may obscure these microfissures. Third, these microfissures may be peculiar to the in vitro model. Elastic tissue, such as the normal arterial wall or some soft plaques, is displaced and not cut. Thus, there appears to be differential removal of hard atherosclerotic plaque.

In two recent clinical studies, the use of high-speed rotational atherectomy was evaluated in patients with coronary artery disease. In patients with diffuse disease (lesions >10 mm), the success rate was 70%; this was significantly less than the 92% success rate in patients with lesions ≤10 mm.13 None of these patients had adjunct balloon angioplasty. In a cooperative European study, the success rate was 86%; adjunct balloon angioplasty was necessary in two thirds. Twenty-four percent of these lesions were calcified.14

In our study, we confirm the efficacy of rotational atherectomy in treating heavily calcified stenotic coronary arteries. These 28 patients represent a consecutive series of patients treated using rotational atherectomy and then studied by IVUS. These patients had some of the most heavily calcified arteries that we have imaged.
IVUS images after rotational atherectomy show a circular or near-circular lumen, especially in areas of heavy calcification. Three-dimensional reconstruction of these images shows that the lumen is, in fact, cylindrical. Typically, the interface between the residual atherosclerotic plaque and the lumen is smooth. Fissures and/or dissections were uncommon, occurring in only 12 of 28 patients (43%). Significant tissue disruption (dissections only) occurred in eight of 28 patients (29%). This is true regardless of the presence, amount, or distribution of the calcium or whether the atherectomy is followed by balloon angioplasty. When dissections occur, they are typically superficial, are located within an arc of calcified plaque, and have limited axial and circumferential extension. This is in contradistinction to balloon angioplasty of calcified lesions in which dissections, especially extensive dissections, are the rule.14–17 In 15 calcified coronary artery lesions (with an average arc of calcium of 48±74°) treated with balloon angioplasty and studied with IVUS afterward, we found fissures in 15, dissections in 15, extensive dissections in 11, an average number of 1.9±0.7 dissection planes per lesion, and arterial expansion in four.16 In addition, dissections after balloon angioplasty typically occur at the junction of calcified and noncalcified plaque.17 During balloon angioplasty, the calcified deposit acts as a fulcrum for the barotrauma and the edge of the deposit acts as a wedge in creating a cleavage plane.

We have documented that rotational atherectomy causes atherosclerotic plaque tissue removal. However, there was still significant residual plaque averaging 54% of the total arterial (or external elastic membrane) CSA. Quantification of calcium ablation is more difficult. It is not possible to measure lesion calcium CSA; the inner rim of calcium shadows and obscures the full thickness of the calcium deposit. There can be calcium ablation with thinning of the calcified plaque but no measurable change in its arc. Only with full-thickness removal will the arc shrink. Nevertheless, in a small number of patients studied before and after rotational atherectomy, we were able to demonstrate a tendency for the arc of calcium to become smaller.

Arterial expansion, even after adjunct balloon angioplasty, was not seen in any patient regardless of the presence, amount, or distribution of calcium. Furthermore, in patients studied before and after rotational atherectomy, lesion site external elastic membrane CSA did not increase afterward even if adjunct balloon angioplasty was necessary. Because rotational atherectomy can cause intense vasospasm, a residual angiographic stenosis may include a component of spasm. A function of adjunct balloon angioplasty may be to break this vasospasm and restore normal arterial CSA. A study of more patients imaged by ultrasound before rotational atherectomy, after rotational atherectomy but before adjunct balloon angioplasty, and after adjunct balloon angioplasty will be necessary to confirm this hypothesis. The use of a motorized pullback device to move the transducer-tipped catheter facilitates such comparative studies.

Even when rotational atherectomy is not followed by balloon angioplasty, the lumen tends to be larger than the largest burr used. Here, too, there are several potential explanations. First, there may be nonaxial

**Table 2. Five Patients Imaged Both Before and After Rotational Atherectomy**

<table>
<thead>
<tr>
<th>Patient</th>
<th>Atherectomy site</th>
<th>Proximal reference (EEM CSA) (mm²)</th>
<th>EEM CSA (mm²)</th>
<th>Lumen CSA (mm²)</th>
<th>Ca²⁺ (°)</th>
<th>P+M CSA (mm²)</th>
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<tbody>
<tr>
<td>20</td>
<td>Before PTCRA</td>
<td>11.9</td>
<td>10.9</td>
<td>1.3</td>
<td>0</td>
<td>9.5</td>
</tr>
<tr>
<td></td>
<td>After PTCRA</td>
<td>10.9</td>
<td>6.0</td>
<td>0</td>
<td>0</td>
<td>4.8</td>
</tr>
<tr>
<td>22</td>
<td>Before PTCRA</td>
<td>20.3</td>
<td>11.8</td>
<td>1.3</td>
<td>270</td>
<td>10.5</td>
</tr>
<tr>
<td></td>
<td>After PTCRA</td>
<td>11.5</td>
<td>5.6</td>
<td>80</td>
<td>6.2</td>
<td></td>
</tr>
<tr>
<td>24</td>
<td>Before PTCRA</td>
<td>28.4</td>
<td>18.4</td>
<td>1.3</td>
<td>120</td>
<td>17.1</td>
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<td></td>
<td>After PTCRA</td>
<td>18.8</td>
<td>9.5</td>
<td>80</td>
<td>8.9</td>
<td></td>
</tr>
<tr>
<td>27</td>
<td>Before PTCRA</td>
<td>†</td>
<td>*</td>
<td>3.6</td>
<td>360</td>
<td>*</td>
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<td></td>
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<td>23.5</td>
<td>14.9</td>
<td>1.3</td>
<td>95</td>
<td>13.6</td>
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<tr>
<td></td>
<td>After PTCRA</td>
<td>14.7</td>
<td>5.3</td>
<td>70</td>
<td>9.6</td>
<td></td>
</tr>
</tbody>
</table>

EEM, external elastic membrane; CSA, cross-sectional area; P+M, plaque and media; PTCRA, percutaneous transluminal coronary rotational atherectomy.

*Could not measure because dense intimal calcification caused acoustic shadowing of deeper tissue planes.
†Could not measure because lesion site was ostial.
(radial) movement (or shimmy) of the burr and guidewire or of the coronary artery in systole and diastole relative to the burr so that device ablates a larger CSA of atherosclerotic tissue. Second, vasospasm during more rotational atherectomy may cause more tissue-burr contact and plaque removal than in the baseline state. This supports the theory that the role of adjunct balloon angioplasty may be to counteract arterial vasospasm in some patients. Third, large amounts of intracoronary nitroglycerin are given during the procedure to cause pharmacological coronary vasodilatation. Removal of intimal calcium and fibrous tissue may “release” the vessel wall to permit coronary vasodilatation either spontaneously (restoration of “physiological” compensatory dilatation), after nitroglycerin, or after adjunct balloon angioplasty.

The appearance of a coronary artery and its lumen after high-speed rotational atherectomy is very different from its appearance after either balloon angioplasty or directional atherectomy. The sharp, distinct calcium-lumen interface is unique to this procedure. Balloon angioplasty barotrauma affects the artery in different ways depending on plaque composition. Calcified arteries typically dissect, and the lumen-intimal interface shows the effect of extensive tissue disruption. Directional atherectomy appears to work by a combination of mechanisms. Although there may be evidence of barotrauma from the offsetting balloon, characteristic directional atherectomy cuts distort the lumen from cylindrical geometry either radially or axially. After rotational atherectomy, the lumen is almost a perfect cylinder, especially in the areas in which there has been calcium ablation.

Study Limitations

There are several limitations to this study. The patient population is relatively small, most of these patients had heavily calcified target lesions, only five patients were imaged both before and after atherectomy, and only seven were imaged after atherectomy without adjunct balloon angioplasty. Without imaging before and after rotational atherectomy and before and after adjunct balloon angioplasty, it will not be possible to quantify in vivo the differential atheroablation of calcified and soft plaque that has been observed in vitro. Also, it will not be possible to separate atherectomy effect from adjunct balloon angioplasty effect. Most of the target lesions were in proximal locations; 16 patients were imaged when only a 4.9F catheter system was available. Only 11 patients were studied using the motorized pullback device; the ability to assess the effects of rotational atherectomy on axial vessel geom-
tery therefore is limited. External elastic membrane CSA could not be measured in eight patients because of heavy calcification. Likewise, tissue disruption may have been underestimated because of the heavy calcification.

Limitations in Three-dimensional Reconstruction

The algorithm used in this study is thresholding based. With thresholding classification, it is assumed that each volume element (or voxel) contains only one type of tissue. In reality, voxels contain a mixture of tissue types. The echogenicity of the tissue contained within each voxel is volume averaged; the entire voxel is classified in a binary fashion according to the threshold selected as if it contained only one type of tissue. The greatest limitation of volume averaging occurs at tissue-surface interfaces. This makes it difficult to accurately represent surfaces. Furthermore, the operator must pick a fixed threshold. Nevertheless, the surface characteristics of calcified plaque after rotational atherectomy are remarkably consistent and significantly different from the surface characteristics of soft plaque (Figure 9) or of arteries after other transcatheter therapies. Superficial tissue disruption was limited. This was confirmed by planar cross-sectional imaging that has an inherently greater resolution.

Conclusions

High-speed rotational atherectomy causes atheroablation, particularly of calcified atherosclerotic plaque, to create a uniformly cylindrical lumen somewhat larger than the largest burr tip used. Significant tissue disruption is uncommon, and arterial expansion is rare. These findings are independent of the amount or distribution of calcium or of whether rotational atherectomy is followed by adjunct balloon angioplasty.

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