In Vitro Validation of Three-Dimensional Intravascular Ultrasound for the Evaluation of Arterial Injury After Balloon Angioplasty

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Objectives. The hypothesis of this study was that three-dimensional ultrasound imaging would facilitate the evaluation of arterial dissection after balloon angioplasty.

Background. The presence and extent of arterial dissection occurring at the time of balloon angioplasty may be important predictors of abrupt vessel closure or late restenosis.

Methods. Forty-one human arterial segments obtained after death were imaged in an in vitro system at physiologic pressure (80 to 100 mm Hg) before and after balloon angioplasty. Images were acquired with a 20- to 30-MHz mechanical Intravascular ultrasound imaging system (Cardiovascular Imaging Systems) with a constant pullback technique (1 mm/s). Standard 0.5-in. (1.27-cm) video tapes were used for data storage and later playback for analog to digital conversion. Digitized data were reconstructed to three-dimensional images with use of voxel space modeling. The vessels were opened longitudinally and subjected to pathologic examination, photographed and classified histologically as normal, fibrous or calcified. Dissection was defined as a disruption and separation of components of the arterial wall. The length and depth of arterial dissection were evaluated grossly and microscopically.

Results. Of the 41 arteries studied, 36 (88%) exhibited dissection on pathologic examination after balloon angioplasty. Three-dimensional reconstruction of intravascular ultrasound images identified dissection in 31 (92%) of 12 normal, 8 (100%) of 8 fibrous and 11 (69%) of 16 calcified arteries. Excellent agreement between ultrasound and pathologic findings was achieved in the evaluation of length and depth of dissection for histologically normal and fibrous arteries (kappa = 0.72 to 1.0). When the vessels were severely calcified, the agreement was not as good (kappa = 0.27 to 0.56), particularly in detection of small, non-raised intimal flaps.

Conclusions. This histopathologic validation study suggests that three-dimensional intravascular ultrasound imaging facilitates the evaluation of both quantitative and morphologic features of arterial dissection induced by balloon angioplasty. The advantage of three-dimensional intravascular ultrasound is its ability to assess the length and morphology of arterial injury over an entire vessel segment.

Balloon angioplasty has become an accepted, routine treatment of atherosclerotic vascular disease. However, it is known to cause vascular injury with plaque fracture and arterial dissection (1,2). Primary success and late restenosis appear to be directly related to the extent of vascular damage occurring at the time of balloon angioplasty (3,4). Ip et al. (3) reviewed the role of vascular injury in syndromes of accelerated atherosclerosis. They defined several types of injury, based on the depth of damage, ranging from functional alterations of endothelial cells without disruption (type 1) to endothelial denudation with injury through the internal elastic lamina to media (type 2) or adventitia (type 3). Autopsy studies (5,6) of patients who died early after balloon angioplasty have shown that more extensive arterial injury (types 2 and 3) may be the inciting event leading to acute vessel closure and late restenosis. Despite technologic advances in the performance of balloon angioplasty, acute closure occurs in approximately 5% of cases (7) and serial angiographic studies (8) have confirmed restenosis rates of up to 50% by 1 year.

Arterial dissection and morphologic changes in the plaque are not well visualized or accurately quantified with contrast angiography. With intravascular ultrasound imaging, the vessel wall, plaque and intraluminal structures can be studied in greater detail (9). The tomographic intravascular ultrasound images are particularly suited to analysis by computerized algorithms that allow three-dimensional reconstruction of two-dimensional images (10-12). These three-dimensional images allow the investigator to view an entire arterial segment or region of interest in multiple views. Instead of mentally reconstructing a series of single tomographic slices, the interventionalist can now visualize
changes occurring over a defined segment. Accordingly, the purpose of this study was to determine if three-dimensional intravascular ultrasound imaging enhances the assessment of arterial injury after balloon angioplasty by identifying both the length and the depth of arterial injury.

Methods

Preparation of specimens. Postmortem human peripheral arterial segments (iliac, femoral, carotid) were obtained at autopsy and stored in 10% neutral buffered formalin (n = 35) or normal saline (n = 6) solution at 3°C. Excess surrounding tissue was dissected free to a similar extent in all vessels and discarded. An in vitro apparatus was designed to allow control of intraarterial pressure, as well as the rate of pullback of the ultrasound catheter. Figure 1 is a diagrammatic representation of this in vitro apparatus. Note that the arterial segments were secured between two Touey-Borst connectors containing rubber diaphragms that maintained the integrity of the pressurized system.

Ultrasound imaging. Imaging was carried out in a saline bath under nonpulsatile physiologic pressures (80 to 100 mm Hg) maintained with use of a sphygmomanometer-pressure bag system. The ultrasound catheter was continuously pulled back at a constant rate of 1 mm/s throughout imaging. The pullback was performed on a motorized platform to which the ultrasound motor unit was attached. Each blood vessel was marked with a suture to allow orientation of the superior aspect of the artery and to facilitate comparison of images with pathologic evaluation. Imaging was performed with use of a mechanical intravascular ultrasound imaging system from Cardiovascular Imaging Systems (CVIS). Both 8F 20-MHz and 5F 30-MHz catheters were used, and images were stored on standard 0.5-in. (1.27-cm) video tape. The arteries were imaged both before and after balloon angioplasty. Standard peripheral angioplasty balloons, exceeding arterial size, were selected to induce dissection. (Balloon outer diameters ranged from 6 to 10 mm and balloon lengths were 4 cm.)

Pathologic analysis. After ultrasound images were obtained, the vessels were visually inspected, then carefully cut open longitudinally away from the sites of dissection. (Dissection was defined as a disruption and separation of components of the arterial wall.) The number of gross dissections, the length of the dissections and the depth of involvement (intima, media, adventitia) were identified visually, measured and recorded by two investigators and independently by a third investigator. Where discrepancies arose, agreement was reached by consensus of the three investigators. The arteries were then photographed to provide a permanent record and allow later review and comparison with histopathologic findings.

Arteries were numbered, decalcified (if necessary) and transversely sectioned for routine light microscopic examination of hematoxylin-eosin-stained sections. The arteries were classified histologically in blinded manner by a pathologist (M.C.F.) as normal, fibrous or calcified. Normal arteries contained no significant atherosclerotic changes. Fibrous arteries demonstrated atherosclerotic changes consisting of intimal smooth muscle proliferation in a dense collagenous stroma with some lipid present. Calcified arteries contained these atherosclerotic changes with either focal or diffuse calcifications. The depth of arterial dissection assessed on gross examination was compared with that on histologic transverse cross sections and agreement on depth was reached by the consensus of three investigators.

Ultrasound analysis. Three-dimensional reconstruction was performed on a series or stack of two-dimensional ultrasound images with the technique of voxel modeling (10). Pixels or picture elements have X and Y dimensions, whereas voxels or volume elements are extensions to three-dimensional space enclosing a domain with X, Y and Z dimensions. Two-dimensional images at a rate of 6 to 10 frames/s are obtained at a constant pullback to create a stack of tomographic images. Analog to digital conversion was performed (at rates of up to 7.5 frames/s) either on line (n = 6) or later from playback (n = 35) of 0.5-in. video tapes. The acquired data, or captured data set, of up to 128 images are reviewed, and the catheter and surrounding "ring down" artifact is "blanked out" by the software (11,12). Figure 2 demonstrates the stages of three-dimensional reconstruction beginning with a series of two-dimensional images, such as the one shown in Figure 2A. Processing begins with the creation of a set of revolving images with the axis centered around the catheter (Fig. 2B), allowing the investigator to view the vessel along the entire length of the pullback. The next step creates a boundary description by setting a threshold within a region of interest.
Table 1. Histopathologic Correlation of Three-Dimensional Ultrasound in 41 Arterial Segments

<table>
<thead>
<tr>
<th>Dissection</th>
<th>Normal Arteries (n = 15)</th>
<th>Fibrous Arteries (n = 8)</th>
<th>Calcified Arteries (n = 18)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Pathol</td>
<td>3-D</td>
<td>Pathol</td>
</tr>
<tr>
<td>Dissection</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0</td>
<td>3</td>
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</tr>
<tr>
<td>1</td>
<td>10</td>
<td>10</td>
<td>4</td>
</tr>
<tr>
<td>&gt;1</td>
<td>2</td>
<td>3</td>
<td>4</td>
</tr>
<tr>
<td>Length (mm)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>&lt;5</td>
<td>1</td>
<td>2</td>
<td>0</td>
</tr>
<tr>
<td>≥5</td>
<td>11</td>
<td>11</td>
<td>8</td>
</tr>
<tr>
<td>Depth</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Intima</td>
<td>6</td>
<td>6</td>
<td>4</td>
</tr>
<tr>
<td>Media</td>
<td>6</td>
<td>6</td>
<td>4</td>
</tr>
</tbody>
</table>

Pathol = pathologic classification; 3-D = three-dimensional ultrasound imaging classification.

Finally, rendering produces the three-dimensional image views that can be formatted whole as a cylinder or cut. The sagittal section shown in Figure 2C demonstrates thin inner and outer rings surrounding an echolucent central ring. These findings are present in the two-dimensional and the revolved images, and have been reproduced by three-dimensional processing. The computer program is "user friendly" because of the mouse-driven graphic user interface. Images can be rotated or sectioned in an almost infinite number of ways to evaluate both inner and outer surfaces of the vessel. Gray scale can be adjusted to highlight a particular region of interest (10-12).

Statistical analysis. The ultrasound data were reviewed by the three investigators (K.M.C., J.C.P., R.J.S.). Images were assessed for the following variables: 1) presence of dissection (0, 1, >1), 2) length of dissection (<5 mm, ≥5 mm), and 3) depth of dissection (extension to intima, media, adventitia). Agreement was reached by consensus of the three investigators. Histopathologic correlation was carried out on subgroups according to histologic type and variable. The kappa statistic (13) was used to compare the magnitude of agreement in categoric histopathologic interpretations among different methods (ultrasound and pathology). A kappa of 0 indicates only chance agreement between two methods, and a kappa of 1 indicates perfect agreement (14). In general, values >0.75 indicate excellent agreement, values of 0.4 to 0.75 indicate good agreement and values <0.4 indicate marginal agreement (14). For purposes of statistical testing, the null hypothesis (H0) associated with this statistic is that there is no similarity between the imaging methods, and that any observed similarity is due to chance (H1: kappa = 0). A one-sided alpha of 0.05 was taken as the threshold for statistical significance with respect to the alternative hypothesis (H1: kappa > 0).

Results

There were 41 peripheral arterial segments (5 elastic and 36 muscular). On histologic study 15 arteries were normal, 8 exhibited fibrous plaques and 18 were calcified. Table 1 summarizes the data for each of the histologic subtypes and postangioplasty variables. The majority (36 [88%]) of 41 arteries demonstrated dissections on gross and light microscopic pathologic examination. When pathologically confirmed arterial dissection was present, ultrasound imaging correctly identified its presence in 11 (92%) of 12 normal, 8 (100%) of 8 fibrous and 11 (69%) of 16 calcified arteries. Of the five arteries without pathologic dissection, three were normal and two were calcified on histologic study.

Normal arteries. Figure 3A demonstrates a three-dimensional reconstructed ultrasound image of an ultrasonically normal artery after balloon angioplasty. The thin linear raised echodensity in the 9 o'clock position was classified by ultrasound as an intimal flap ≥5 mm in length. The histologic section (Fig. 3B) confirms that the artery was a normal muscular artery with an intimal flap. The flap was confirmed
to be >5 mm in length by measurement of the gross specimen. Figure 4A demonstrates a sagittal section of three-dimensional intravascular ultrasound reconstruction. The linear echolucency traversing the length of the segment corresponds to the linear dissection seen grossly (Fig. 4B). A separate linear dissection noted grossly is not seen on the three-dimensional image because of the choice of sagittal section.

Of the 15 histologically normal arteries, most demonstrated a single dissection that was >5 mm in length and medial or adventitial. There was one false positive ultrasound study in which an intimal flap >5 mm was suspected but could not be confirmed pathologically. Ultrasound and pathologic findings were discordant in one other case in which a single pathologically confirmed dissection was categorized as multiple dissections by ultrasound. The findings were similar for both muscular and elastic arteries. In Figure 5 a normal elastic (carotid) artery is shown after angioplasty. The two-dimensional ultrasound image (Fig. 5A) reveals extensive dissection to the adventitia that is seen in the 7 o'clock position in the cylindrical three-dimensional reconstruction (Fig. 5B). The histologic section (Fig. 5C) confirms extensive dissection to the adventitia.

Fibrous arteries. All eight fibrous vessels exhibited arterial dissection (single in four and multiple in four). Pathologic study confirmed that all the dissections were >5 mm, whereas ultrasound imaging underestimated the length of dissection in one case. Dissections involved both the media and adventitia in seven of eight cases by ultrasound study and in all eight cases by pathologic study. The discrepancy arose in one case in which ultrasound underestimated the depth of involvement and classified a deeper dissection (involving media) as involving intima only.

Calcified arteries. Of the 18 calcified vessels, 10 had a single dissection, 6 had multiple dissections and two had no dissection. Thirteen of the dissections were >5 mm in length; the other three were <5 mm. In five segments ultrasound imaging did not identify the presence of a dissection (false negative result), but intimal flaps were present on pathologic examination (two were <5 mm, three were...
>5 mm in length). In one case an intimal flap <5 mm was identified by ultrasound but not confirmed pathologically (false positive result).

**Histopathologic correlation.** Table 2 summarizes the histopathologic correlation of the three-dimensional ultrasound data for the normal, fibrous and calcified arteries. Excellent agreement for the identification of dissection and estimation of the length and depth of dissection was achieved for both normal and fibrous subgroups. The kappa values ranged from 0.63 to 1.0 with highly significant p values (when kappa = 1.0 agreement is complete and p values are highly significant, approaching 0). The level of agreement was lower for all variables of the calcified arteries as manifested by the lower kappa values, which ranged from a low of 0.27 in estimating the length of dissection to a high of 0.56 in estimating the depth of dissection. When data in the calcified arteries were further analyzed for dissection, the kappa value for the absence of dissection was 0.1, indicating poor agreement in ruling out the presence of dissection. When dissections were subgrouped by length < or >5 mm, kappa values for dissections <5 mm were lower than those for dissections >5 mm (0.1 vs. 0.47). Finally the deeper dissections, specifically those involving media or adventitia, had higher kappa values than those for intimal flaps, for which kappa values reflected poor agreement, approaching 0.1.

### Table 2. Histopathologic Correlation of Three-Dimensional Ultrasound in 41 Arterial Segments

<table>
<thead>
<tr>
<th>Variable</th>
<th>Normal Arteries ( (n = 15) )</th>
<th>Fibrous Arteries ( (n = 8) )</th>
<th>Calcified Arteries ( (n = 18) )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Kappa</td>
<td>( 0.73 \pm 0.19 )</td>
<td>( 1.0 )</td>
<td>( 0.42 \pm 0.15 )</td>
</tr>
<tr>
<td>Length</td>
<td>( 0.72 \pm 0.18 )</td>
<td>( 1.0 )</td>
<td>( 0.27 \pm 0.15 )</td>
</tr>
<tr>
<td>Depth</td>
<td>( 1.0 )</td>
<td>( 1.0 )</td>
<td>( 0.56 \pm 0.13 )</td>
</tr>
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</table>

**Discussion**

Postangioplasty dissection. This study is the first report to validate the use of three-dimensional, intravascular ultrasound imaging to assess arterial dissection after balloon angioplasty. As with any new imaging technique, particularly when manipulations such as computer enhancement or reconstruction are performed, the findings warrant confirmation. The goal of this study was the histopathologic validation of three-dimensional intravascular ultrasound images. In 41 postmortem arterial segments the presence of dissection was correctly identified by three-dimensional ultrasound in a high percentage of normal (92%) and fibrous arteries (100%). Results in the calcified arteries were lower (69%).

Because the intent of this study from the outset was to study dissections, large balloons were chosen. For this reason only a few arteries \( (n = 5) \) were free of dissection after angioplasty and the majority of dissections were >5 mm long and involved deeper layers (media, adventitia) than is usual. The use of oversized angioplasty balloons larger than those used clinically is likely to have resulted in dissections that do not represent the true depth, extent and degree of injury induced during life. In addition, the effects of formalin fixation reducing elasticity of the arterial walls may have facilitated dissection in the normal arteries. A larger proportion of small intimal flaps could potentially result in lower agreement between ultrasound and histologic
findings. Accordingly, future studies are required to determine the precise sensitivity and specificity of three-dimensional ultrasound for balloon angioplasty-induced arterial dissection.

For normal and fibrous arteries, excellent agreement between three-dimensional ultrasound and histopathologic findings was achieved for the identification of dissection and estimation of length and depth of dissection. The degree of agreement was less when these same variables were studied in calcified arteries. Subgroup analysis identified calcification and superficial dissections as the factors that led to a lower level of agreement.

State of development of three-dimensional ultrasound and limitations. High resolution intravascular ultrasound images are now obtainable with both mechanical and phased array devices. During the past year improvements in the two-dimensional images and the development of powerful computers with sophisticated software packages have made three-dimensional reconstruction feasible. The time constraints of early three-dimensional reconstruction have been eliminated, and such images can now be performed on line (15). Furthermore, the ability to alter thresholds and change gains allows considerable enhancement of images of both dissections and the vessel wall.

A continuous, constant rate pullback provides a precise method of obtaining a series of tomographic images that can be stacked and then reconstructed three-dimensionally. This is the first study to use a motorized system for precise catheter pullback rather than a manual approach. Such a standardized pullback system provides accurate information along the z axis and helps avoid the potential artifact associated with reconstruction of images from manual pullbacks shown in Figure 6. In this example a sudden movement or change in the speed of pullback resulted in distortion in the three-dimensional image. Rosenfield et al. (16) in a preliminary report suggested that the rate of pullback should allow acquisition of at least 15 frames/s for normal vessels and 20 frames/s for diseased vessels. They suggest that these acquisition rates prevent image distortion or blurring and allow longer segments to be reconstructed. Computer systems in use today allow these acquisition rates. With further advances in computer technology, faster sampling rates may lead to further improvements in image quality.

Three-dimensional ultrasound was correlated with pathology as the standard for studying arterial dissection after balloon angioplasty. However, histologic sectioning artifacts can make the in vitro diagnosis of arterial dissection difficult. Dissections occurring in vivo frequently contained red cells and fibrin deposits under the flap, and these served as reliable indicators that dissection occurred before death. To minimize errors in overestimating the presence and extent of dissection, both histologic and gross pathologic evaluation of

Figure 6. Sagittal sections of a three-dimensional reconstructed intravascular ultrasound image demonstrating an artifact (arrow) created by a change in catheter speed in the middle of the pullback.

Figure 7. A. Three-dimensional reconstructed image in sagittal format revealing signal loss (arrows) due to the presence of calcific deposits. B. Cylindric format of three-dimensional ultrasound image demonstrating signal dropout (arrows) due to catheter housing artifact.
all arterial segments were carried out. The findings demonstrate a high level of agreement between three-dimensional ultrasound and histopathologic findings in the identification of arterial dissection, as well as the estimation of length and depth of involvement. Agreement was best for histologically normal vessels and for those with fibrous atherosclerotic changes, and less good for calcified vessels.

Calcium present. A major impediment to the penetration of ultrasound signals, leading to acoustic shadowing or signal dropout beyond it. Figure 7 demonstrates a three-dimensional reconstructed arterial segment from a calcified vessel. Considerable signal loss is evident on the three-dimensional images. This problem may account for false positive as well as false negative results, depending on the amount and distribution of the calcific deposits in the arterial wall. Despite the lesser agreement in all categories of the calcified vessels, the lowest kappa values were noted in the identification of small (<5 mm) intimal flaps. In this study the severely calcified peripheral arteries utilized often contained a circumferential ring of calcium. In the clinical setting most arteries treated with angioplasty have less calcification or more focal calcium, making the interpretation of three-dimensional ultrasound images easier.

An issue related to clinical application is the safety of intravascular ultrasound imaging, especially when catheters are used to traverse lesions in the coronary circulation. However, the technique appears to be safe, and many investigators (17-19) have performed intravascular ultrasound imaging both before and after intracoronary intervention. As catheter size decreases and combined imaging/interventional devices (20,21) are developed, the small risk of injury may be reduced further.

In clinical use a mechanically timed pullback system should have greater precision than could be expected with a manually timed pullback. In addition, for in vivo intracoronary cases in which there is considerable motion of the catheter with each cardiac cycle, gating of the images may be required to maintain three-dimensional image alignment in all axes.

Comparative studies. The work of Tobis et al. (22) provides the only other study of intravascular ultrasound imaging before and after balloon dilation with pathologic correlation. In their in vitro study, 17 human atherosclerotic arteries were imaged with a 20-MHz mechanical intravascular ultrasound catheter before and after balloon angioplasty. They found that tears were typically located at the thinnest region of the plaque where it interfaced with the normal arterial wall. Furthermore, dissection planes occurred between the plaque and the internal elastic lamina. In 11 of 13 of these arterial segments, when matched ultrasound and histologic sections were available, ultrasound imaging accurately predicted the histologic presence of tears.

Pathologic studies (1,2) of the effects of balloon angioplasty on the plaque and arterial wall have demonstrated plaque fractures and dissection clefts that have been linked to the angioplasty procedure itself. However, a study by Isner et al. (23) refutes this assumption by reporting similar pathologic findings in 49% of 70 patients studied at autopsy who did not undergo balloon angioplasty during life.

Our findings support the use of intravascular ultrasound imaging to identify the presence of plaque fracture and arterial dissection after balloon angioplasty. They cannot resolve the controversy just described, but three-dimensional reconstruction allows further characterization of arterial injury by providing an estimate of its linear extent and evaluating the depth of involvement. It is these factors that may have an important impact on the success of the angioplasty procedure itself. Although formalin fixation may alter the imaging characteristics, most specimens were studied in the fixed state because of ease of storage and safety purposes.

Future clinical applications. This study of three-dimensional ultrasound imaging suggests that this technique may be useful in the clinical setting. With on-line reconstruction of three-dimensional images, arterial segments of interest can be visualized in three dimensions before and after endovascular intervention and the three-dimensional reconstruction can be almost immediately (within 90 s) compared with the contrast angiogram (Fig. 8). We performed three-dimensional reconstruction in vivo in one patient with a significant iliac arterial stenosis. After digital contrast angiography (Fig. 8A), an 8F 20-MHz intravascular ultrasound catheter (Diasondics) was passed over a guide wire with fluoroscopic guidance to the area of stenosis and then across the lesion. A manual timed pullback of the catheter was then performed and the images were reconstructed on line to produce three-dimensional images of the arterial segment at the site of atherosclerotic narrowing (Fig. 8, B to D). Standard balloon angioplasty was then performed and digital contrast angiography performed when angiographic success was achieved (Fig. 8E). After removal of the balloon catheter, the ultrasound system was readvanced across the area of dilation, and a second timed pullback was performed. Three-dimensional analysis was again performed on line (Fig. 8, F to H). The lumen diameter at the site of the stenosis improved, and two small linear superficial dissections were noted. The digital angiogram revealed a hazy appearance and wall staining suggestive of, but not diagnostic of, dissection. The additional information provided at the time of the procedure not only confirmed the success of the procedure itself, but also assured the operator that the dissection was small and unlikely to lead to an adverse outcome.

Conclusions. Three-dimensional intravascular ultrasound imaging holds promise for the evaluation of patients after balloon angioplasty or other interventional procedures. More accurate qualitative and quantitative classification of arterial injury may improve on the angiographic predictors of early and late success. Large dissections that may have a high risk of acute closure could be identified in the cardiac and vascular catheterization laboratory. Knowing this, the operator may consider other therapeutic options, such as stent implantation, to avert a potential early failure. With
Figure 8. A. Digital contrast angiogram of the iliac artery showing the site of stenosis. Panels B to D are the two-dimensional, revolved (longitudinal) and three-dimensional reconstruction of the area of stenosis. The catheter (c) is in the center of the lumen and the guide wire (arrows) can be seen in the center of the three-dimensional reconstructed image. E. After balloon angioplasty, the digital angiogram revealed an increased lumen diameter result; however, wall staining (arrows) was noted at the site. Panels F to H again demonstrate the two-dimensional, revolved and three-dimensional reconstructed ultrasound images. F. A linear echodensity can be seen in the lumen in the two-dimensional image (arrow) and is clearly demonstrated to be a dissection in the revolved image (G). The three-dimensional reconstructed segment (H) shows not only this dissection (lower arrow) but a smaller one just superior (upper arrow); it also confirms the increased lumen diameter after angioplasty.
continued technologic improvements, three-dimensional ultrasound may become an important addition to intravascular imaging and has the potential to favorably influence the outcome of endovascular intervention.

References


