Three-dimensional Reconstruction of Intracoronary Ultrasound Images

Rationale, Approaches, Problems, and Directions

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Abstract Although intracoronary ultrasonography allows detailed tomographic imaging of the arterial wall, it fails to provide data on the structural architecture and longitudinal extent of arterial disease. This information is essential for decision making during therapeutic interventions. Three-dimensional reconstruction techniques offer visualization of the complex longitudinal architecture of atherosclerotic plaques in composite display. Progress in computer hardware and software technology have shortened the reconstruction process and reduced operator interaction considerably, generating three-dimensional images with delineation of mural anatomy and pathology. The indications for intravascular ultrasonography will grow as the technique offers the unique capability of providing ultrasonic histology of the arterial wall, and the need for a three-dimensional display format for comprehensive analysis is increasingly recognized. Consequently, three-dimensional imaging is being rapidly implemented in the catheterization laboratories for guidance of intracoronary interventions and detailed assessment of their results. However exciting the prospects may be, three-dimensional reconstructions at present remain partially artificial because the true spatial position of the imaging catheter tip is not recorded, and shifts in its location and curves of the arterial lumen result in pseudoreconstructions rather than true reconstructions. In this report, we address the principles of three-dimensional reconstruction with a critical review of its limitations. Potential solutions for refinement of this exciting imaging modality are presented. (***Circulation*. 1994;90:1044-1055.**)

Key Words • ultrasonics • tomography • imaging

Although the experienced medical mind is capable of three-dimensional conceptualization of complex structural morphology and pathology, objective computerized three-dimensional reconstructions would facilitate both qualitative and quantitative analysis and enhance our diagnostic capabilities. Intracoronary ultrasound provides tomographic images of the arterial lumen and wall components that are displayed in a sequential fashion on the monitor screen. Conceptualization of the spatial relations of these components and their pathology requires repeated review of the recorded tomographic images. Computerized three-dimensional reconstruction allows the display of these tomographic images in their longitudinal relation to the proximal and distal segments and provides an objective spatial picture and a potential gateway to quantification. Other clinical advantages are a better understanding of the pathoanatomy of the vessel wall and the application of new parameters of wall dynamics, both of which may help in guiding intracoronary interventions. Recently, real-time three-dimensional reconstruction algorithms have become available for on-line routine clinical use and allow the arterial segment to be viewed in sagittal and cylindrical display formats. In this report, we review the different approaches to three-dimensional reconstruction and discuss the initial clinical results and potential problems.

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Three-dimensional Reconstruction Techniques

Three-dimensional reconstruction requires a series of sequential steps: image acquisition, image digitization and segmentation, and three-dimensional reconstruction and display (Table 1).

Image Acquisition

A sequence of cross-sectional images of a coronary segment must be correctly sampled so that the relation of the successive images to one another is known. After digitization of the cross-sectional images, the coronary segment can be reconstructed in three-dimensional space by applying the selected algorithm and is then displayed on the monitor screen, resulting as a volumetric image with dimensions in the X, Y, and Z planes. The most critical step is the correct acquisition of the sequence of the cross-sectional images, with their optimal gray scale. Two techniques can be used: (1) a continuous pullback at a known rate along the examined coronary segment by the use of motorized systems to achieve a uniform speed[1] and (2) a sequential acquisition of adjacent cross sections, interspaced by constant intervals by a displacement sensor[2,3] (Fig 1). The ultrasound imaging catheter is introduced through a small, sterile, disposable sensing unit. The movement of the catheter activates a rotating wheel that converts the linear movement into an electronic pulse train signal so that advancement or withdrawal of the catheter is precisely digitized and wirelessly

TABLE 1. Process for Three-dimensional Reconstruction of Intracoronary Ultrasound Images: Basic Steps

Step 1	Image acquisition
Step 2	Image digitization and segmentation
Step 3	Three-dimensional reconstruction
Step 4	Display and analysis

registered by a sterilizable unit to which the sensing unit is mounted. The relative distance is mixed in the display of the corresponding cross section on the monitor screen to provide real-time position information. A built-in interface allows direct connection of this device to a computer system to enable three-dimensional reconstruction. By reading digital position data from a displacement sensor, a set of echographic slices can be automatically acquired at a desired increment (minimum interval: 0.1 mm).

Image Digitization and Segmentation

The sampled cross-sectional images are stored into a digital format using a small-pixel matrix of at least 512×512 for optimal resolution and 8-bit gray scale to preserve high definition of the image. It should be realized that a trade-off always exists between the resolution of the image and the speed of computer processing. Image segmentation is the next necessary step. Three different algorithms are presently used for three-dimensional reconstructions (Table 2). In the wire-mesh model, the contours separating different structures are manually or automatically defined and the contours of adjacent cross sections are interconnected by straight lines. This method is far from ideal for representation of structures with a complex geometry, and the method is now obsolete. In the threshold method, a threshold intensity is defined to obtain binary images in which all the voxels with an intensity above or below the threshold are considered to belong or not to belong to the object to be reconstructed. The advantage is that this approach permits complete automation for assessment of geometry, but gray scale information on

TABLE 2. Algorithms for Three-dimensional Reconstruction of Intracoronary Ultrasound Images

Model	Advantages	Disadvantages
Wire mesh	Simple structures require small computer memory	Not suitable for objects of complex geometry
Binary image	Fully automated	No definition of wall components
Gray scale	Visualization of wall components	Large computer memory Long processing time

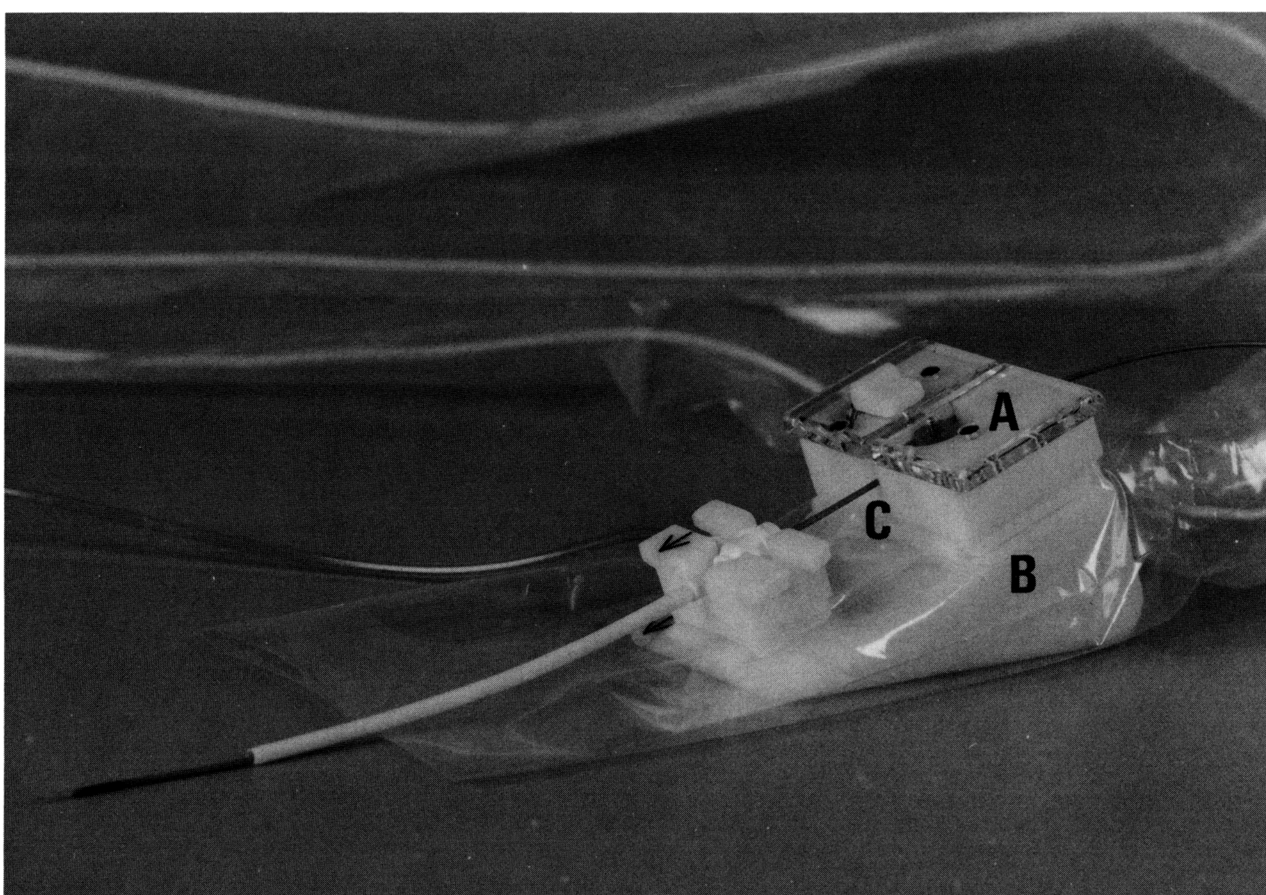

FIG 1. Catheter displacement–sensing device showing the sterile sensing unit (A), which is attached to the registration part in a sterile plastic sheet (B). The ultrasound imaging catheter (C) is passed through the sensing unit into the intra-arterial sheath.

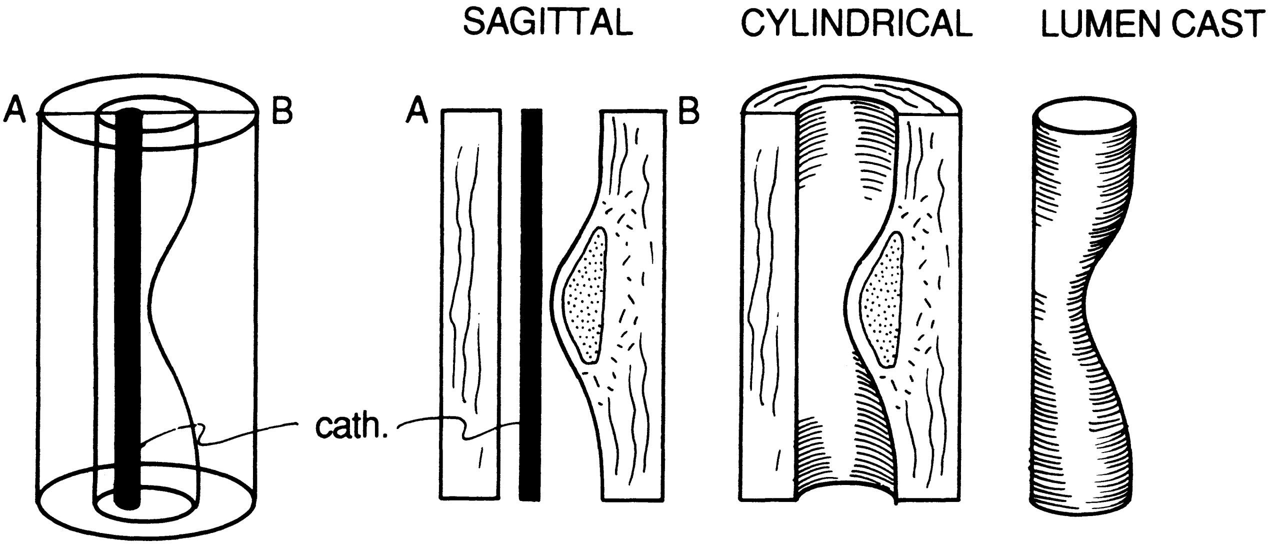

FIG 2. Display formats of three-dimensional reconstructed segments of arteries from intracoronary ultrasound images. Any longitudinally cut plane from the voxel space containing the reconstructed arterial segment can be selected. If plane A-B is selected, lumen patency and wall components are displayed in the sagittal format. In the cylindrical format, luminal topography and wall components are visualized. Lumen cast format shows lumen morphology isolated from the arterial wall.

wall pathology is lost. Both methods and have been largely replaced by methods preserving individual volumetric pixel gray scale, a method known as voxel modeling.[4] This method allows detailed visualization of the gray scale of the wall components, and three different presentation formats are used: (1) the cylindrical or hemicylinder format, (2) the sagittal or revolve format, which supplements the cylindrical format, and (3) the lumen cast format (Fig 2). The specific advantages of each of these formats are presented in Table 3. The availability of arterial wall data in a cubic matrix allows volumetric quantification of individual wall components including lumen, plaque, and media. Technical progress has been so rapid that high-resolution, three-dimensional reconstruction with detailed gray scale has now become an almost on-line reality.

In our center, initial research in three-dimensional reconstruction of vascular images has been focused on the automatic detection of the boundaries of the lumen and the media. This approach is a preliminary but crucial step for the three-dimensional quantification of lumen and wall pathology. After a temporal smoothing of consecutive frames to reduce blood echogenicity and enhance the lumen borders, a semiautomatic method of contour detection is used to define the leading edge of the blood vessel wall interface as well as the media interface. The method is based on the application of a minimum cost algorithm and on the use of dynamic

TABLE 3. Display Formats for Three-dimensional Reconstruction of Intracoronary Ultrasound Images: Format

Display Format	Advantage
Cylindrical format	Allows direct viewing of luminal surface
Sagittal format	Allows direct assessment of lumen patency and arterial wall pathology
Lumen cast format	Allows instantaneous analysis of the lumen over entire segment length

programming techniques to find an optimal contour based on a circular model. The method of analysis developed at our center for contour detection requires manual tracing to outline the boundaries of the endothelial contour and the interface between the intima and the hypoechoic media in the first cross section. The manually traced contours are then used as a model to define the search region and resample the rest of the image into a polar coordinate format. For each frame, the edge strength of both the lumen border and media is calculated separately in all resampled pixels and used to define the optimal contours through the data representing the strength of the edges (Fig 3). This method has been validated in vitro[5] and in vivo[6] and has been successfully used for automatic assessment of systolic and diastolic changes of lumen cross-sectional area.

Three-dimensional Reconstruction

The voxel modeling method is applied to three-dimensionally reconstruct the lumen and plaque, including the detected contours.[7] To visualize a three-dimensional object on a monitor screen, the reconstructed artery must be projected to a two-dimensional space by a rendering procedure. Three elements can be calculated from the voxel model: (1) the distance of the voxel element, (2) the gradient vector of the voxel surface, and (3) the original gray texture. Combining these three elements in the shading process enables visualization of the depth and orientation of the arterial object and the original echo intensity. Fig 4 shows a reconstructed three-dimensional image in which the echolucent media surface is clearly visible because of the preserved gray values of the echographic slices. When the media interface is indicated automatically or manually in the image segmentation procedure, the lesion volume can be encoded with different colors to optimize visualization of the lesion and normal arterial wall (Fig 5). It should be realized, however, that the three-dimensional reconstructions are partially artificial and not true spatial reconstructions, since the wall structures are not represented in their correct

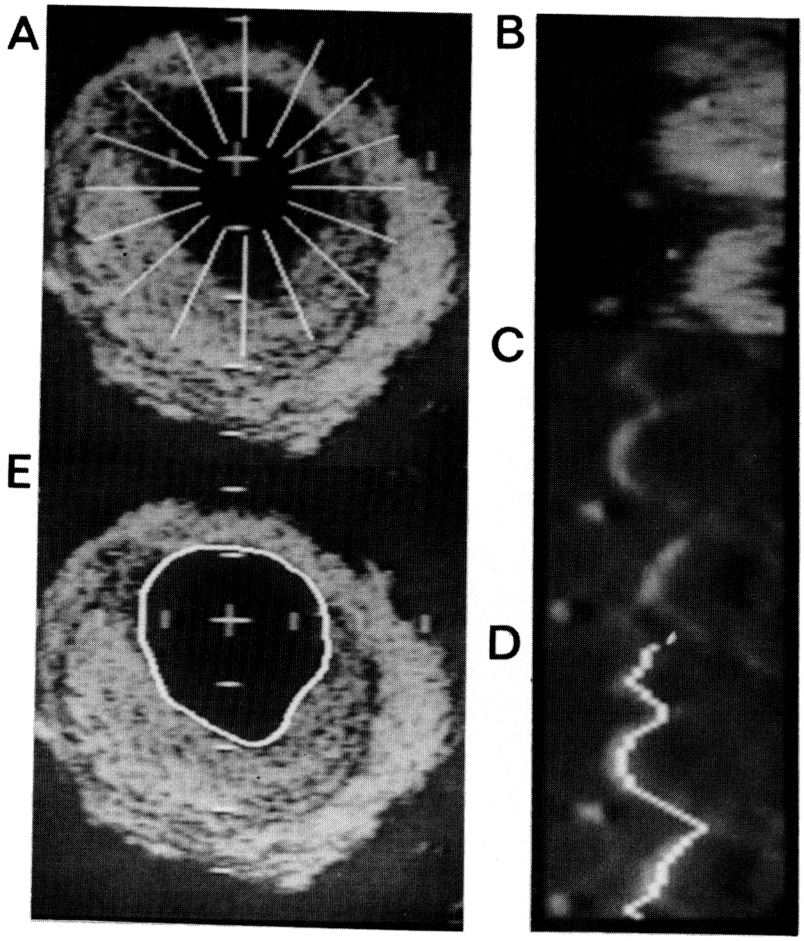

FIG 3. Principle of semiautomatic boundary detection in intracoronary ultrasound images. A, Resampling of the image along scan lines; B, ultrasound data in polar format; C, cost matrix displaying low-cost values with high gray levels; D, path determined by minimum-cost algorithm; and E, luminal contour derived by transferring path back to the image coordinates.

geometry because of the straight catheter line display. Indeed, shifts in catheter position in the lumen or angulation of the lumen during the acquisition are not accounted for by presently available reconstruction systems (Fig 6).

Display Formats

When the three-dimensional reconstruction process is complete, various modalities of display are possible, including derived two-dimensional images (transverse, sagittal, and oblique views) and true three-dimensional images (cylindrical—both closed- and open-shell format—and luminal cast formats) (Fig 2). While each provides a unique view of the lumen and mural components, their combination is often required to convey a comprehensive perspective. In particular, the linking of sagittal with cross-sectional (two-dimensional) views offers an oriented landscape for both quantitative and qualitative analysis, which can be exploited to overcome device-related echo drop-out. Cylindrical images are the most effective display format for qualitative examination of the vessel wall, providing a panorama of the longitudinal relation of complex dissections and ensuring optimal deployment of stents. While luminal casts provide a unique perspective on the physiological end point of advanced atherosclerosis—a three-dimensional view of luminal encroachments—the value of this display format will remain limited until techniques for spatial correction for catheter displacement have been mastered.

Observer Interaction

The degree of observer interaction and influence of the final image varies according to the algorithm deployed for three-dimensional reconstruction (see Table 2). With the simpler algorithms (wire mesh and binary), less user interaction is required, and the analysis should become more reproducible and objective. With the gray scale algorithm, preservation of the original echographic information enabling differentiation of the individual mural components can be achieved by the experienced operator. Algorithms for automated blood speckle subtraction are currently under development, such as shown in Fig 3. However, the reliability of automated edge detection will be dependent on the image characteristics and the gray scale threshold selected by the operator.

Quantitative Analysis

A potential advantage of the voxel modeling is that each voxel is directly related to the volume element of the three-dimensional object. Appropriate segmentation algorithms would allow calculation of volume and quantification of lesion distribution longitudinally. However, the plaque-media interface can only be detected automatically in images of optimal quality and with minimal disease. Therefore, manual interaction for plaque-media border identification is necessary in most instances, which is a tedious and a time-consuming procedure. The sites of the minimal lumen area and diameter, maximal lesion deposit, and highest area of

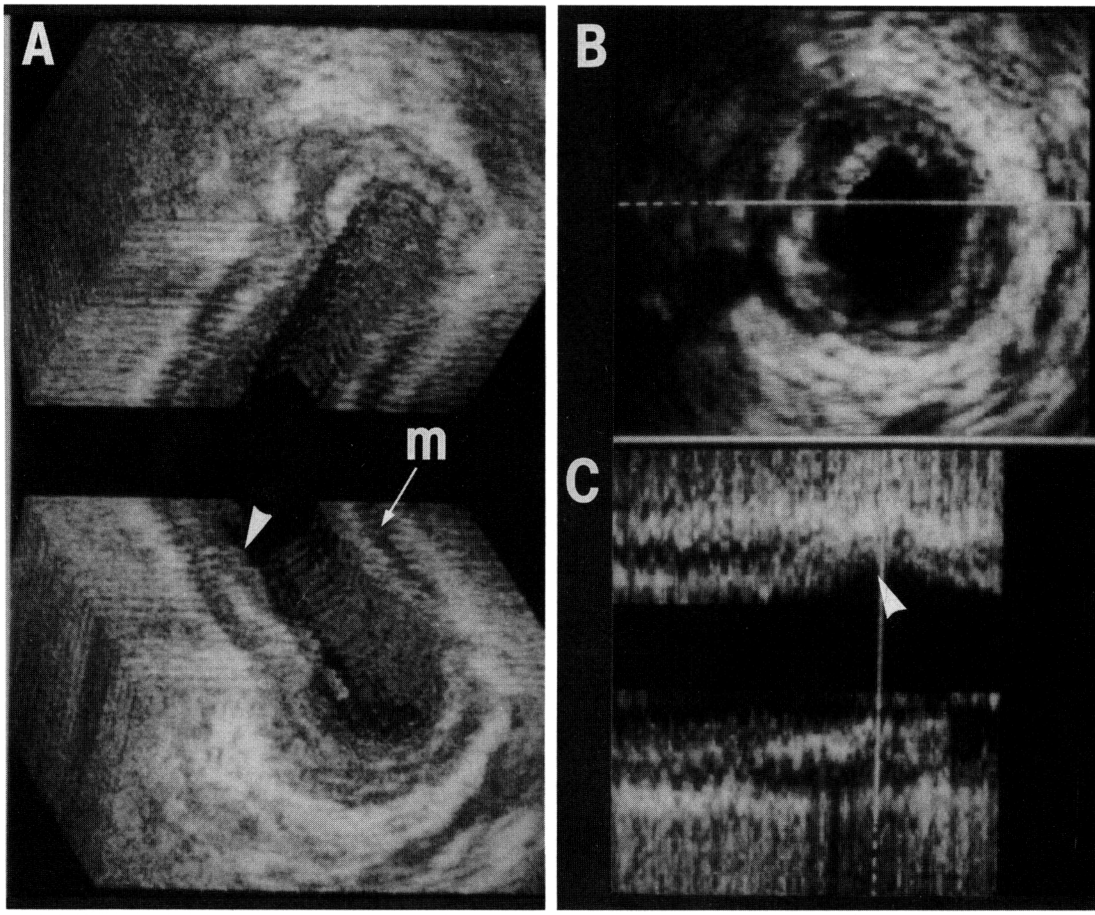

FIG 4. Three-dimensional reconstruction of a proximal segment of the left anterior coronary artery examined immediately after directional atherectomy. Residual plaque and position of the cuts (arrows) are clearly visible after three-dimensional reconstruction, showing the arterial segment as two open hemicylinders (A). Cross section (B) at the site of one of these cuts gives only limited information on the area and extent of plaque removal. A cut is also seen in the longitudinal format display (lower right in C). Note detailed information on wall pathology and its distribution as a result of tissue gray value encoding. Longitudinal architecture of the media (m) and plaque are clearly seen.

obstruction can be determined. Other parameters such as the length of the calcified lesion and the length of the lesion dissection/rupture could provide vital information for quantitative assessment of the diseased vessel and evaluation of the effect of therapeutic intervention (Fig 5). A practical interactive approach for plaque volume calculation is shown in Fig 7.

Limitations and Possible Solutions

Several factors may cause problems in three-dimensional reconstruction (Table 4). The major critical factor in obtaining adequate results of the three-dimensional reconstruction is the image quality of the basic cross sections. An unreliable delineation of the intimal border and absence or incomplete circumferential detection of the hypoechoic media preclude three-dimensional reconstruction and subsequent quantitative measurements of lumen and plaque volumes. This is particularly a problem when calcium shadowing obscures the underlying wall.

The use of cross-sectional images distorted by nonuniform rotation of a mechanically rotated beam may create distortion in the reconstructed image, and plaque may be either underestimated or overestimated in size[8] (Fig 8). Three-dimensional reconstruction of branching points presents a particular challenge for three-dimensional reconstruction techniques, as the side branches cannot be tracked very far because of the limited depth of the echo penetration. However, plaque accumulation at branching points (where atherosclerosis is often most pronounced) can be detected easily in the reconstructed image, and the position of side branches can be an important landmark to obtain consistent focal acquisitions in serial examinations. Noncoaxial positioning of the catheter tip in a bending lumen will overestimate the cross-sectional area of the lumen. The systematic overestimation of lumen diameter or area by ultrasound compared with angiography in most studies may be partially explained by this phenomenon.[9] Another factor is cardiac motion during the cardiac cycle, which may cause shifts in catheter position in the lumen (Fig 6); therefore, ECG-gated acquisition of the images should be considered when large-sized coronary arteries are studied. Structure shadowing by the guide wire artifact present in some catheter systems can mask a sector of 30° of the arterial segment (Fig 10). Catheters must be designed so that no artifacts are present in the image. Another critical factor concerns the correct acquisition of the spatial sequence of cross-sectional images. A fixed distance between adjacent cross sections is mandatory but difficult to achieve even with sophisticated means such as a motorized pullback or a displacement-sensing device. Bends in the ultrasound catheter may induce differences between movement of the tip and that of the proximal end of the catheter. Another potential source of error is the rotation of the catheter during pullback, causing a longitudinal mismatch between the orientation of sequential images.

Curvatures of the vessel lumen or catheter may also induce a predictable distortion of the three-dimensional image that is reconstructed along a straight line connecting successive cross sections (Fig 9). As a result, expansion or compression of plaques may occur, leading to overestimation or underestimation of the volumes measured from the reconstructed image. While spatial location systems for the catheter tip are not commercially available at present, reconstruction of the spatial pathway of the ultrasound catheter tip during image acquisition by biplane fluoroscopy may be feasible in the near future. Recent experimental and clinical validation studies of such spatially correct three-dimensional reconstruction using biplane digital cinefluoroscopy indicate that the reliability of coronary measurements can be significantly improved by radiographic spatial correction with less than 4 minutes' additional patient study time.[10]

The use of a miniaturized receiving antenna located at the tip of the ultrasound catheter combined with external electromagnetic radiating antennas in planes perpendicular to the catheter axis has also been proposed as a possible method to detect the orientation of the ultrasound catheter.[11] These approaches may allow the reconstruction of the pathway of the catheter during a pullback in three-dimensional space and be combined with the three-dimensional reconstruction algorithm.

The Dotter effect of the first generation of intracoronary imaging catheters presents a significant problem in the examination of stenoses and small vessels. The possibility of stenosis modification should be borne in mind in the analysis of luminal diameters of <1.6 mm. The problem of Dotter effect from these catheters is not limited to quantification of the true lumen: in a study using 4.8F and 3.5F catheters, intracoronary ultrasound failed to detect 15% of dissections after balloon angioplasty.[12] This failure to detect dissections was believed to be most likely due to a Dotter effect. The advent of the new generation of 2.9F catheters is expected to reduce the Dotter-related problems of overestimation of coronary luminal stenoses and small vessels and the underestimation of compressible mural components.

The limited resolution and failure to image structures close to the catheter—"near-field artifact"—can occur with multielement electronic systems, which have numerous transducer elements mounted circumferentially. This problem may be overcome by the use of single-element mechanical systems, whereby the distance from the core transducer to structures in contact with the catheter is extended.

In terms of cost and manpower considerations, the estimated cost for a software program for three-dimensional reconstruction is currently in the region of $6000. Clearly, this price would be expected to fall when large numbers are sold and additional competitors enter the market. The minimal hardware requirement for processing of the digitized data is a 486DX personal computer, while the options for storage media continue to expand, depending on budgetary restrictions and preference for compression/decompression modes. Motorized pullback systems are likely to cost approximately $5000. The manpower requirements are also considerable. If real-time reconstruction is required in the catheterization laboratory to immediately affect clinical decision making, then any delay in data assimilation or postprocessing will cost the accumulative man-hours of the entire catheterization laboratory team. A typical time required for three-dimensional reconstruction of a 17-mm coronary segment (pulled back at 0.5 to 1 mm/s) is 90 seconds. Alternatively, three-dimensional reconstruction for research purposes may be performed effectively at a later time outside the catheterization laboratory, requiring the presence of only one person. As each year goes by, considerable advances are made in computational speed (586DX chips, coprocessors, higher clock speeds, data storage formats with faster read-write times). It is likely, therefore, that man-hour requirements in 1996 will be significantly less than in 1994.

However, it appears that despite all these potential problems, intracoronary ultrasound is superior to angiography for the qualitative assessment of atherosclerosis and offers the unique potential for its quantification in the future. It is likely that it will become the gold standard in the assessment of peripheral and coronary arterial pathology (Figs 4 and 10).

Clinical Experience

Assessment of Lumen and Plaque Volumes

While three-dimensional reconstruction plays a valuable role in all of the clinical applications listed in Table 5, its greatest potential contribution perhaps may be in the study of progression-regression of preclinical atheromatous disease. While significant regression is unlikely to occur at sites of advanced atherosclerosis containing extensive calcification and fibrosis, regression frequently occurs in coronary segments containing early coronary atherosclerotic disease. Glagov et al[13] have shown that vessels accommodate early atherosclerotic plaque by peripheral (outward) expansion of the vessel wall without angiographically detectable luminal narrowing (see Fig 10). Three-dimensional intravascular ultrasound is sensitive to the detection and quantification of such early atherosclerotic disease and thus may be used to both select and analyze coronary segments for the study of progression-regression.

Rosenfield et al[14] proposed the application of automated edge detection algorithms for the analysis of a three-dimensional lumen cast. With this method, a rapid assessment of the minimal cross-sectional area during interventions on peripheral arteries was possible on-line in 19 patients.

Matar et al[15] use a motorized pullback handle to obtain a uniform distance between consecutive cross sections in the examination of 10 in vitro arterial specimens and of the coronary arteries of 16 patients. The volumes of the reconstructed lumen correlated well with histology measurements and the results of biplane quantitative angiography. The measurement of plaque volume would allow a direct assessment of the progression-regression of atherosclerosis as a result of pharma-

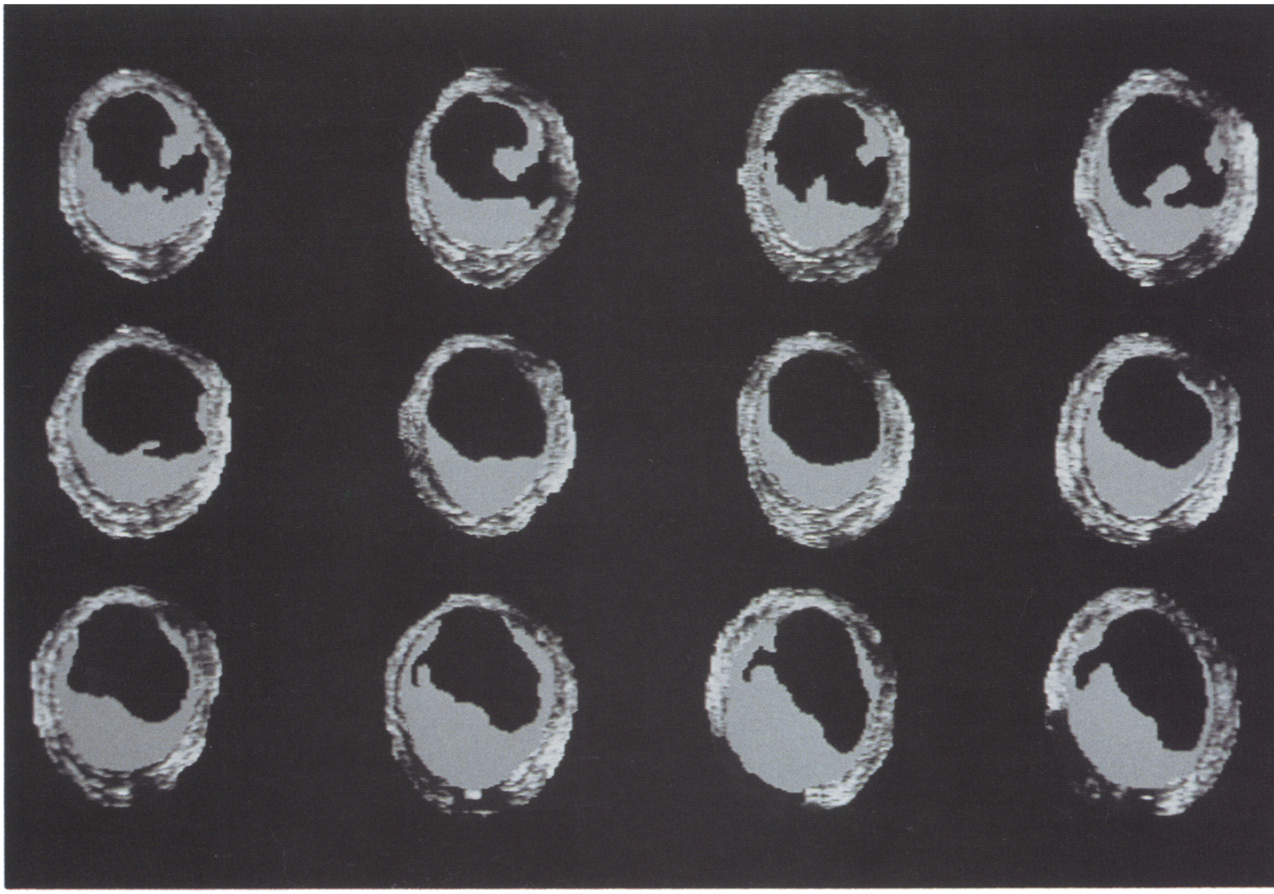

FIG 5. Facing page. Top, Consecutive cross sections at 2-mm intervals of a segment of a femoral artery after balloon angioplasty. Plaque areas are clearly depicted after the image segmentation procedure for object identification during three-dimensional reconstruction. Eccentric plaque and a dissection are seen. Bottom, Cut-open view of the reconstructed artery shows lesion dissection and eccentric distribution of plaque along the segment. Brightness of voxels is computed from both the gradient vector of the voxel and its depth to create depth perception.

cological or dietary interventions[16,17] and the effect of physical and mechanical interventions. Galli et al[18] compared the measurements of plaque volume based on the planimetry of consecutive cross sections at a fixed interval with the measurements obtained with a direct three-dimensional reconstruction with the true plaque volume of a vessel phantom. Plaque volumes measured with three-dimensional reconstruction overestimated the true plaque volume of the phantom, whereas accurate measurements were obtained from direct planimetry of the echographic cross sections. Detailed information on saphenous vein graft aneurysm structure was recently published providing clues on its development.[19]

Assessment of Interventions

Intracoronary ultrasound has the potential to quantify plaque composition as well as dimensions. Such information is of value in the selection of the type and size of an interventional device and the guidance of the interventional procedure itself. Calcification of the target coronary lesion has been reported in 76% to 83% of the patients undergoing coronary angioplasty.[20,21] A higher incidence and an increased depth and circumferential extension of the dissection after balloon dilatation have been reported in calcified when compared with noncalcified plaques.[21-23] In the presence of diffuse subendothelial calcifications, a higher incidence of complications and a smaller amount of retrievable material was observed after directional coronary atherectomy.[21] Only with three-dimensional intravascular ultrasound, however, the longitudinal and radial extension depth of the calcific plaque components can be assessed along the entire segment to be dilated.

Intravascular ultrasound has been used before and after interventions to identify the mechanism of balloon dilatation. Wall stretching and wall dissection have been reported as the main operative mechanism of balloon angioplasty in coronary[24,25] and peripheral arteries.[26] A significant plaque compression (absolute reduction of plaque area) has been reported more recently.[27] A possible reason of these discrepancies is the unavoidable difference in the examined arterial cross section before and after interventions. The measurement of plaque volume after three-dimensional reconstruction along the entire dilated segment can provide a more

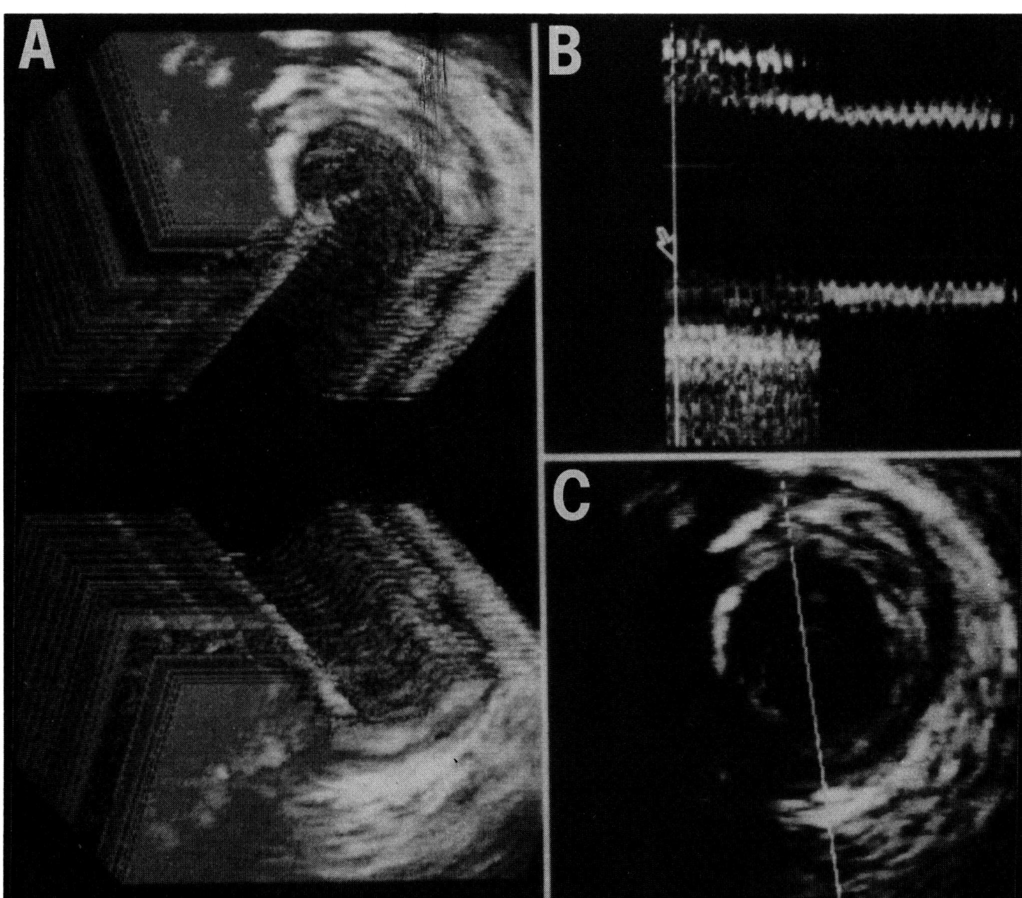

FIG 6. Three-dimensional reconstruction of a coronary segment with superficial fibrocalcific atherosclerosis (A). Cyclic oscillation of the fibrocalcific area is best seen on the sagittal display and results from shifting catheter position in the lumen (B). Underlying structures are not displayed as a result of the shadowing effect shown on the tomographic cross section in C.

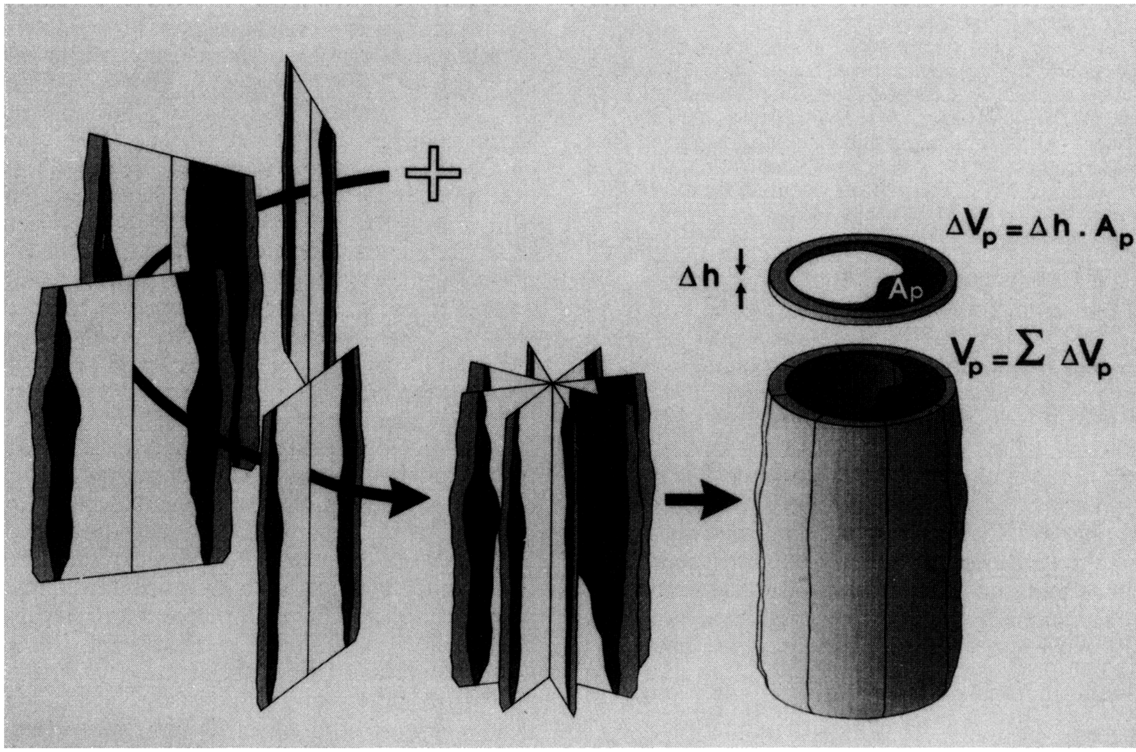

FIG 7. Schematic: Simplified approach to calculate plaque volume from intravascular ultrasound images and three-dimensional voxel space. Four longitudinal cross sections are selected around the circumference of the coronary segment (see Fig 4B). In each of these, the blood-intima and plaque-media borders can be traced manually. Interpolation of the structure boundaries at each cross-sectional plane allows the calculation of the plaque volume (Vp) in the reconstructed segment.

reliable assessment of the plaque changes brought about by the dilation process.

Pathology studies have shown that diffuse plaque disruption is one of the predominant mechanisms of lumen enlargement after balloon angioplasty.[28] In the presence of complex intraluminal flaps, angiography shows the presence of filling defects in a minority of cases. Intravascular ultrasound is more sensitive than angiography in the detection of intraluminal flaps after coronary interventions.[29-32] The standard cross-sectional display, however, does not show the longitudinal relation of these complex intraluminal flaps. On-line three-dimensional reconstruction would allow an immediate assessment of the wall changes induced by vascular interventions. The prognostic value of these findings in the prediction of immediate outcome and restenosis has been reported recently.[33]

From the on-line and off-line analyses of the intravascular ultrasound examination of 52 peripheral and 22

TABLE 4. Three-dimensional Reconstruction of Intracoronary Ultrasound Images: Limitations

Related to image quality
Poor definition of the intimal border (blood echogenicity)
Poor definition of the plaque-media border (absence of hypoechoic media)
Shadowing by calcium
Noncoaxial position of the catheter tip (elliptical distortion)
Nonuniform rotation of the transducer
Related to acquisition
Vessel curvatures may induce distortion of the reconstructed image
Catheter tip position shifts in the lumen
Twisting of the catheter during pull-back induces mismatch between orientation of sequential two-dimensional images
Luminal area may change throughout the cardiac cycle

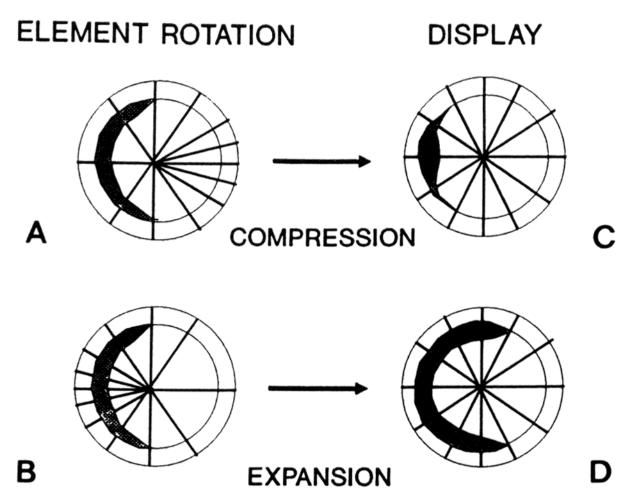

FIG 8. Diagram explaining the principle of image distortion induced by nonuniform rotation of the ultrasound source (rotating crystal or mirror). Cross-sectional images A and B are displayed assuming a constant circumferential speed of rotation of the transducer so that plaque of the same dimensions (gray area in A and B) is displayed smaller (C) or larger (D) when the rotation is faster or slower in the corresponding radiants.

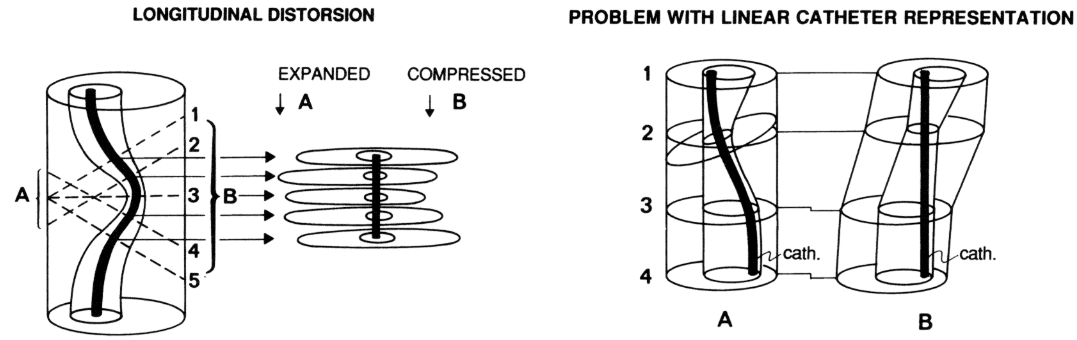

FIG 9. Diagrams showing potential distortion in three-dimensional reconstructed images of arterial segments as a result of curvatures of the catheter (or artery) and its position in the lumen. Curvature will result in sampling of a smaller area (A) at the concave site of the catheter; a larger area (B) is sampled at its convex site. This will result in an expanded area A and a compressed area B on the display. Cross sections representing oblique cuts are larger on the display, and their longitudinal relation is distorted because of the display of the catheter path as a straight line. This problem is amplified in diagram B. Also note that the reconstructed segment is longer than in reality as a result of the straight catheter display.

coronary arteries, Rosenfield et al[34,35] have shown that sagittal reconstructions facilitate the analysis of dissections and the detection of tunneling of a false lumen in the recanalization of total occlusions. Coy et al[36] have reported an excellent agreement between three-dimensional reconstruction of intravascular ultrasound images and pathological findings in the evaluation of length and depth of post–balloon angioplasty dissection in arteries without diffuse intimal calcification.

Recent reports[37,38] have shown the usefulness of computer-assisted three-dimensional reconstruction in the identification of the true lumen and of the length of dissection before stenting as bail-out for extensive dissection after coronary angioplasty. After stenting, three-dimensional reconstruction allows the measurements of longitudinal and radial dimensions of these poorly radiopaque vascular prostheses.[39] The normal appearance of the stent in contact with the vessel wall has been described and defined as a "cobblestoned" appearance. The technique has been shown to facilitate the detection of an incomplete expansion of the stent. Segments with an incomplete apposition between stent and vessel wall, a condition with increased risk of acute thrombosis, are more easily identified.

Intravascular ultrasound has been reported as a clinically useful tool in the guidance and assessment of the

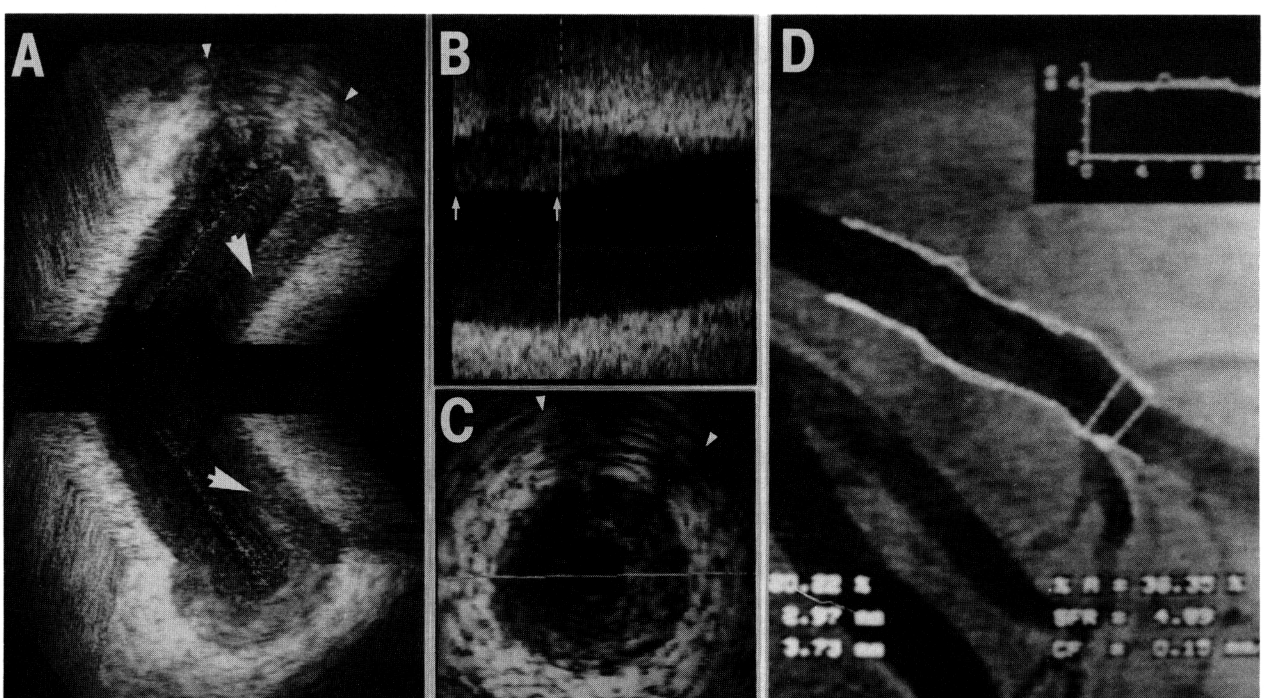

FIG 10. A, Three-dimensional reconstruction of a segment of the left anterior descending coronary artery showing a large eccentric soft plaque (large arrows). The longitudinal extent is also clearly seen in the sagittally cut plane shown on B, also demonstrating the wide open lumen of the segment. Note the localized vessel wall expansion compensating for the encroachment of plaque on the lumen (localized Glagov effect). Some Dotter effect caused by the catheter is also seen (small arrows). Eccentric plaque is visualized in the cross section obtained in the middle of the plaque (C). Strut artifact in the 11 to 2 o'clock position obliterates wall structure information over a segment of 30° (sectors indicated by small arrows) and affects the reconstructed image (small arrows in A). D, Coronary arteriogram of the reconstructed segment. A wide patent lumen is present, and no information on the wall pathology is obtained.

TABLE 5. Clinical Applications of Three-dimensional Reconstruction of Intracoronary Ultrasound Images

Quantification of vascular dimensions
Luminal and plaque volumes
Study of restenosis and progression-regression
Interventional guidance
Selection of interventional device type and size
Avoidance of atherectomy in presence of extensive calcification
Dimensions and type of stent to be developed
Guidance of interventional procedures
Assessment of persistent plaque burden and direction of atherotome cuts
Optimize stent deployment to ensure symmetrical and uniform stent inflation
Comprehensive evaluation of interventional mechanisms and complications
Examination of complex spiral dissections for bailout stenting

results of directional atherectomy[24,40] (Fig 4). Recent reports have shown that three-dimensional reconstruction facilitates the orientation of the cutter in relation to side branches and the detection of deep cuts or spiral cuts from rotation of the atherectomy catheter during cutting.[41] The clinical utility of intravascular ultrasound in planning and guidance of a variety of transcatheter treatment modalities has been reported in 88 patients. Mintz et al[42] have suggested a specific usefulness in these cases of on-line three-dimensional reconstruction. A more negative experience has been reported by Ferguson et al.[43] The therapeutic strategy was influenced by intravascular ultrasound in 39% of the cases, but no changes in the planned strategy were decided based on the results of the three-dimensional reconstruction of the echographic cross sections. Initial experience with three-dimensional reconstruction indicates that complications such as dissection are readily detected and quantified.

Future Directions

Three-dimensional reconstruction of intravascular ultrasound images has great potential for the quantitation of volumetric changes of lumen and atherosclerotic plaque. This opens horizons for studying the natural history of atherosclerosis and will become the principal method to study the progression and regression of atherosclerosis in the future. Longitudinal views show the coronary segment architecture currently unavailable from the original tomographic images and multiple orthogonal views not available from angiography. Real-time intracoronary ultrasound images can be combined with guide wire high fidelity pressure and flow velocity recordings and will allow detailed studies of coronary physiology and physical properties of the vessel wall. Clearly, including longer arterial segments from three-dimensional reconstructions would further improve the reliability of results. Recent developments in on-line reconstruction combined with complex computer algorithms, which calculate the stress distribution in a plaque on the basis of its composition and spatial architecture, may guide interventional device selection and predict both the results and likelihood of complications.[44]

Conclusions

Intracoronary ultrasonic imaging provides unique tomographic images of luminal morphology and mural pathology. By virtue of the complex spatial distribution of arterial atherosclerotic disease, a three-dimensional display format is mandatory for comprehensive assessment. This is of particular value in the guidance of therapeutic interventions and assessment of both the immediate and long-term results. Recent developments in computer technology have significantly increased the practicality of three-dimensional intracoronary ultrasound, which now is rapidly becoming an integral component of interventional procedures in the catheterization laboratory. However, many persistent limitations must be solved before it can be implemented as a reliable tool for clinical decision making.

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References

1. Mintz GS, Keller MB, Fay FG. Motorized IVUS transducer pull-back permits accurate quantitative axial measurements. *Circulation.* 1992;86(suppl I):I-323. Abstract.
2. Pasterkamp G, Post MJ, Mali WP, Bom N, Borst C. From which segment of the artery is this IVUS cross section? Two methods for localization: fluoroscopy and displacement transducer. *J Am Coll Cardiol.* 1993;21:192A. Abstract.
3. Gussenhoven EJ, Li W, van den Lugt A, van Stujen MLJ, Stigter CMM, The SHK, van Egmond F, Mali WPTM, Bom N. Accurate displacement sensing device provides reproducible intravascular ultrasound images. *J Am Coll Cardiol.* 1993;21:119A. Abstract.
4. Kitney RI, Moura L, Straughan. 3-D visualization of arterial structures using ultrasound and voxel modeling. *Int J Card Imaging.* 1989;4:135-143.
5. Wenguang L, Gussenhoven WJ, Zhong Y, The SHK, Di Mario C, Madretsma S, van Egmond F, de Feyter PJ, Pieterman H, van Urk H, Rijsterborgh H, Bom N. Validation of quantitative analysis of intravascular ultrasound images. *Int J Card Imaging.* 1991;6:247-254.
6. Di Mario C, The SHK, Madretsma S, van Suylen RJ, Wilson R, Bom N, Serruys PW, Gussenhoven WG, Roelandt JRTC. Detection and characterization of vascular lesions by intravascular ultrasound: an in-vivo correlative study with histology. *J Am Soc Echocardiogr.* 1992;19:135-146.
7. Li W, Bosch JG, Zhong Y, van Urk H, Gussenhoven EJ, Mastik F, van Egmond F, Rijsterborgh H, Reiber JHC, Bom N. Image segmentation and 3D reconstruction of intravascular ultrasound images. *Acoustic Imaging.* 1993;20:489-496.
8. Ten Hoff H, Korbijn A, Smit TH, Klinkhamer JFF, Bom N. Imaging artifacts in mechanically driven ultrasound catheters. *Int J Card Imaging.* 1989;4:195-199.
9. Ge J, Erbel R, Görge G, Gerber T, Brennecke R, Seidel I, Reichert T, Meyer J. Intravascular ultrasound imaging of arterial wall architecture. *Echocardiography.* 1992;9:475-483.
10. Evans JL, Kok-Hwee NG, Vonesh MJ, Cusick DA, Morales RE, Tommasso CL, Meyers SN, Roth SI, Kramer BL, McPhearson D. Spatially correct three-dimensional reconstruction of intracoronary ultrasound: further validation and initial patient studies. *J Am Coll Cardiol.* 1993;21:2:181A. Abstract.
11. Aretz HT, Gregory KW, Martinelli MA, Gregg RE, LeDet EG, Haase WC. Ultrasound guidance of laser atherectomy. *Int J Card Imaging.* 1991;6:231-237.
12. Görge G, Erbel R, Gerber T, Ge J, Kearny P, Ruprecht HJ, Meyer J. Dissections after PTCA: comparison angiography–intravascular ultrasound. *Eur Heart J.* 1993;14(suppl):25. Abstract.
13. Glagov S, Weisenberg E, Zarins CK, Stankunavicius K, Kolettis GJ. Compensatory enlargement of various human atherosclerotic coronary arteries. *N Engl J Med.* 1987;316:1371-1375.

14. Rosenfield K, Kaufman J, Losordo DW, Isner JM. Lumen cast analysis: a quantitative format to expedite on-line analysis of 3D-intravascular ultrasound images. *J Am Coll Cardiol.* 1992; 19:115A. Abstract.
15. Matar FA, Mintz GS, Douek PC, Leon MB, Popma JJ. Three-dimensional intravascular ultrasound: a new standard for vessel lumen volume measurement? *J Am Coll Cardiol.* 1992;19:382A. Abstract.
16. Lassetter JE, Krall RC, Moddrelle DS, Jenkins RD. Morphologic changes of the arterial wall during regression of experimental atherosclerosis. *Circulation.* 1992;86(suppl I):I-518. Abstract.
17. Gupta M, Connolly AJ, Zhu BQ, Sievers RE, Sudhir K, Sun YP, Parmley WW, Fitzgerald PJ, Yock PG. Quantitative analysis of progression and regression of atherosclerosis by intravascular ultrasound: validation in a rabbit model. *Circulation.* 1992; 86(suppl I):I-518. Abstract.
18. Galli FC, Sudhir K, Kao AK, Fitzgerald PJ, Yock PG. Direct measurement of plaque volume by three-dimensional ultrasound: potential and pitfalls. *J Am Coll Cardiol.* 1992;19:115A. Abstract.
19. Ennis BM, Zientek DM, Ruggie NT, Billhardt RA, Klein LW. Characterization of a saphenous vein graft aneurysm by intravascular ultrasound and computerized three-dimensional reconstruction. *Cathet Cardiovasc Diagn.* 1993;25:328-331.
20. Mintz GS, Douek P, Pichard AD, Kent KM, Satler LF, Popma JJ, Leon MB. Target lesion calcification in coronary artery disease. *J Am Coll Cardiol.* 1992;20:1149-1155.
21. Honye J, Mahon DJ, White CJ, Ramee SR, Wallis JB, Al-Zarka A, Tobis MJ. Morphological effects of coronary balloon angioplasty in vivo assessed by intravascular ultrasound imaging. *Circulation.* 1992;85:1012-1025.
22. Fitzgerald PJ, Ports TA, Yock PG. Contribution of localized calcium deposits to dissection after angioplasty: an observational study using intravascular ultrasound. *Circulation.* 1992;86:64-70.
23. Potkin BN, Keren G, Mintz GS, Douek PC, Pichard AD, Satler LF, Kent KM, Leon MB. Arterial response to balloon coronary angioplasty: an intravascular ultrasound study. *J Am Coll Cardiol.* 1992;20:942-951.
24. Kimura BJ, Fitzgerald PJ, Sudhir K, Amidon TM, Strunk BL, Yock PG. Guidance of directional coronary atherectomy by intracoronary ultrasound imaging. *Am Heart J.* 1992;124:1385-1369.
25. Tenaglia AN, Buller CE, Kisslo KB, Stack RS, Davidson CJ. Mechanisms of balloon angioplasty and directional coronary atherectomy as assessed by intracoronary ultrasound. *J Am Coll Cardiol.* 1992;20:685-691.
26. The SHK, Gussenhoven EJ, Zhong Y, Li W, Egmond F van, Pieterman H, van Urk H, Gerritsen P, Borst C, Wilson RA, Bom N. Effect of balloon angioplasty on femoral artery evaluated with intravascular ultrasound imaging. *Circulation.* 1992;86:483-493.
27. Losordo DW, Rosenfield K, Pieczek A, Baker K, Harding M, Isner JM. How does angioplasty work? Serial analysis of human iliac arteries using intravascular ultrasound. *Circulation.* 1992;86: 1845-1858.
28. Waller BF. Coronary balloon artery dissections: "the good, the bad, and the ugly." *J Am Coll Cardiol.* 1992;20:701-706.
29. Tobis JM, Mallery JA, Mahon D, Lehmann K, Zalesky P, Griffith J, Gessert J, Moriuchi M, McRae M, Dwyer ML, Greep N, Henry WL. Intravascular ultrasound imaging of human arteries in vivo. *Circulation.* 1991;83:913-926.
30. Nissen SE, Gurley JC, Grines CL, Booth DC, McClure R, Berk M, Fisher C, DeMaria AN. Intravascular ultrasound assessment of lumen size and wall morphology in normal subjects and patients with coronary artery disease. *Circulation.* 1991;84:1087-1099.
31. Werner GS, Sold G, Buchwald A, Wiegand V. Intravascular ultrasound imaging of human coronary arteries after percutaneous transluminal angioplasty: morphologic and quantitative assessment. *Am Heart J.* 1991;122:212-220.
32. Gussenhoven WJ, Frietman P, The SHK, van Egmond FC, van Suylen F, Lancée CT, van Urk H, Roelandt J, Bom N. Assessment of medial thinning in atherosclerosis with intravascular ultrasound. *Am J Cardiol.* 1991;68:625-632.
33. Tenaglia AN, Buller CE, Kisslo KB, Phillips HR, Stack RS. Intracoronary ultrasound predictors of adverse outcomes after coronary artery interventions. *J Am Coll Cardiol.* 1992;20:1385-1390.
34. Rosenfield K, Losordo DW, Ramaswamy K, Isner JM. Three-dimensional reconstruction of human coronary and peripheral arteries from images recorded during two-dimensional intravascular ultrasound examination. *Circulation.* 1991;84:1938-1956.
35. Rosenfield K, Kaufman J, Pieczek A, Langevin RE, Razvi S, Isner JM. Real-time three-dimensional reconstruction of intravascular ultrasound images of iliac arteries. *Am J Cardiol.* 1992;70:412-415.
36. Coy KM, Park JC, Fishbein MC, Laas T, Diamond GA, Adler L, Maurer G, Siegel RJ. In vitro validation of three-dimensional intravascular ultrasound for the evaluation of arterial injury after balloon angioplasty. *J Am Coll Cardiol.* 1992;20:692-700.
37. Cavaye DM, White RA, Lerman RD, Kopchock GE, Tabbara MR, Cormier F, French WJ. Usefulness of intravascular ultrasound imaging for detecting experimentally induced aortic dissection in dogs for determining the effectiveness of endoluminal stenting. *Am J Cardiol.* 1992;69:705-707.
38. Schryver TE, Popma JJ, Kent KM, Leon MB, Mintz GS. Use of intracoronary ultrasound to identify the true coronary lumen in chronic coronary dissection treated with intracoronary stenting. *Am J Cardiol.* 1992;69:1107-1108.
39. Mintz GS, Leon MB, Popma JJ, Kent KM. Three-dimensional reconstruction of endovascular stents. *J Am Coll Cardiol.* 1992; 19:224A. Abstract.
40. Yock PG, Fitzgerald PJ, Linker DT, Angelsen BAJ. Intravascular ultrasound imaging guidance for catheter-based coronary interventions. *J Am Coll Cardiol.* 1991;17:39B-45B.
41. Smucker ML, Kil D, Sarnat WS, Howard PF. Is three-dimensional reconstruction a gimmick or a useful clinical tool? Experience in coronary atherectomy. *J Am Coll Cardiol.* 1992;19:115A. Abstract.
42. Mintz GS, Leon MB, Satler LF, Kent KM, Pichard AD. Preintervention ultrasound imaging influences transcatheter coronary treatment strategies. *Circulation.* 1992;86(suppl I):I-323. Abstract.
43. Ferguson JJ, Krishnaswami A, Turner SA, Kardesch D, Perin EC, Willerson JT, Fish RD. The clinical utility of intravascular ultrasound: three-dimensional image reconstruction and color mapping of ultrasound images. *Circulation.* 1992;86(suppl I):I-705. Abstract.
44. Lee RT, Loree HM, Cheng GC, Lieberman EH, Jaramillo N, Schoen FJ. Computational structural analysis based on intravascular ultrasound imaging before in vitro angioplasty: prediction of plaque fracture locations. *J Am Coll Cardiol.* 1993;21:777-782.