Arterial Imaging With a New Forward-Viewing Intravascular Ultrasound Catheter, II
Three-Dimensional Reconstruction and Display of Data

Kok-Hwee Ng, MSEE; James L. Evans, MD; Michael J. Vonesh, MSEE; Sheridan N. Meyers, MD; Terry A. Mills, BS; Bonnie J. Kane, BS; William N. Aldrich, BS; Yue-Teh Jang, PhD; Paul G. Yock, MD; Michael D. Rold, BS; Sanford I. Roth, MD; David D. McPherson, MD

Background  Current intravascular ultrasound (IVUS) catheters provide transverse imaging at the level of the ultrasound transducer. This limits imaging to large-diameter segments without critical atherosclerotic narrowings. We have developed a prototype 20-MHz forward-viewing IVUS catheter that provides two-dimensional sector imaging distal to the catheter tip. A present limitation of this technique is that the catheter must be manually rotated to obtain multiple longitudinal views required to integrate the segment into a three-dimensional matrix. To overcome this, we have developed an algorithm that reconstructs these multiple two-dimensional forward-viewing IVUS images into a three-dimensional matrix for more complete depiction of the segment distal to the ultrasound catheter. This algorithm allows display and multidimensional slicing of the three-dimensional reconstruction.

Methods and Results  To test our algorithms, five arterial segments (three canine aortas, two human femoral arteries) were evaluated in vitro. In each segment, 36 forward-viewing longitudinal slices were collected, digitized, processed, and reoriented to produce a three-dimensional reconstruction (3DR) matrix. The matrix data were sliced into parallel transverse sections and compared with morphometric interpretation of histological sections (Histo). As a result, image data could be reconstructed for a distance of 2.0 cm ahead of the catheter. 3DR easily demonstrated wall and luminal morphology and provided transverse IVUS images comparable to the histological specimens. A good correlation was noted between Histo- and 3DR-determined luminal diameters (LD) and luminal areas: 3DR LD = 1.4 Histo LD – 0.4, r = 0.86; 3DR LD = 0.7 ± 0.20 cm (mean ± SD); and Histo LD = 0.7 ± 0.13 cm.

Conclusions  These preliminary data demonstrate the feasibility of 3DR of forward-viewing IVUS data. This method allows rapid, detailed analysis of diseased arterial segments previously unavailable with standard IVUS and may permit better targeting of interventional techniques. (Circulation. 1994;89:718-723.)

Key Words: • ultrasound • imaging • atherosclerosis

E valuation of the extent and severity of atheroma in vivo has recently been aided by the development of high-frequency ultrasound transducers. High-frequency ultrasound (both epicardial and intravascular) uses small ultrasound probes that are placed within or upon the vascular tree and is capable of examining the extent and severity of atheroma. These techniques provide high resolution of lumen and wall.1-8 With these imaging devices, investigators are able not only to determine the extent and severity of atheroma but also to evaluate the effects of atheroma modification (both medical and interventional) on atheroma mass and resultant vessel geometry after intervention.9-14 Thus, for the first time, methods are available to evaluate atheroma morphology, such that qualitative and quantitative decisions concerning the extent and severity of atherosclerosis can be made.

Currently available intravascular ultrasound (IVUS) catheters are designed to provide a 360° tomographic view of a vascular segment at the distal end of the imaging transducer. This requires that the catheter be accessible to the site of atherosclerotic disease, which is often characterized by luminal narrowing or occlusion caused by plaque formation. IVUS catheter miniaturization has thus become important in the evaluation of critical atherosclerosis. However, difficulties in catheter size miniaturization, such as loss of image quality and catheter durability, present a limitation to this approach.

A more novel approach to the problem of catheter accessibility is to design a forward-viewing IVUS catheter. Such a device would provide a forward-viewing image for a certain depth along the long axis of a vessel, enabling imaging of a stenosed vascular segment located ahead of the catheter. A forward-viewing imaging device might decrease vascular trauma, since it would not cross critical atherosclerotic narrowings. We have developed a prototype forward-viewing IVUS catheter with Cardiovascular Imaging Systems (Sunnyvale, Calif).15 This catheter images in a sector plane ahead of the transducer, providing a longitudinal view of a vascular segment up to a depth of 2 cm. Appreciation of vascular morphology is restricted when imaged in a two-dimensional plane.
Arterial Imaging With Forward-Viewing IVUS, II

Ng et al

Methods

Materials

Instrumentation

The prototype forward-viewing IVUS catheter (Cardiovascular Imaging Systems) consists of a 20-MHz single-crystal transducer mounted on a mechanical cam at the tip of the catheter. The catheter is 4 mm in diameter at its distal end. The central core of the catheter is rotated by a motor, and a specially designed link between the core and the cam converts this rotating motion into a 90° sector scan. The ultrasound beam resolution is 0.1 mm in the axial direction and 0.3 mm in the lateral direction. At 20 MHz, the depth of field of the transducer is approximately 2 cm. Fig 1 illustrates a specimen imaged with the present display.

Morphological Specimens

Five postmortem vascular segments were used. They included two human femoral arteries obtained during autopsies and three canine aortas excised after dogs were killed. Specimens were fresh-frozen after harvesting and thawed 24 hours before the start of the experiment. Each specimen was mounted on a tongue blade that served as an identification of the 0° image plane. After mounting, all specimens were immersed in buffered formaldehyde before actual imaging. The specimens were not pressure-fixed during imaging, resulting in variable geometrical configurations.

Methods

Imaging and Data Acquisition

The prototype forward-viewing catheter was mounted on a modified microscope stage in a vertical position. Each vascular segment was clamped vertically at the tongue blade and immersed in a water bath. For imaging, the prototype catheter was lowered into the lumen of the vessel to a desired position. A pin was inserted into the wall of the vessel at the position of the transducer. This position served as a reference for subsequent histological processing of the specimens.

Once the catheter was in position inside the vessel, rotation about the vertical axis was performed with a precision control knob on the microscope stage. A total of 36 sector planes were imaged and video recorded as the prototype catheter was rotated 5° incrementally for a total of 180°. We have previously tested our 3DR technique using a phantom in a water bath and found that 10° incremental rotations were required for accurate geometrical reconstruction (unpublished data). A schematic of this imaging procedure is given in Fig 2, which shows a cylindrical vessel being imaged by the forward-viewing catheter at three different rotational angles. Actual forward-viewing images obtained from a study of a canine arterial segment at four different rotational angles are shown in Fig 3. There is asymmetrical narrowing of this segment at the distal end caused by our histological fixation technique.

Digital Image Processing and Three-dimensional Reconstruction

Forward-viewing video images were digitized in a sequence corresponding to the rotational angle (increasing or decreasing) of the catheter. A rectangular window, with the middle vertical axis coinciding with the axis of the catheter, was defined on the video image and then digitized by use of an 8-bit analog/digital board (ImageComm StatView workstation, ImageComm, Sunnyvale, Calif). The resulting digital images consisted of 256×256 pixels with a range of 256 gray scales.

In the prototype algorithm, lumen and wall interfaces and external wall boundaries on each forward-viewing image were manually traced with an in-house graphics program (Fig 3). Where edge ambiguities occurred, no data were entered. The result of this preprocessing step reduced the original gray-scale images to binary (black-and-white) border definitions and improved the computational efficiency of the reconstruction process.

In the next step, each image frame with traced contours was mathematically oriented according to the angle of catheter rotation within a three-dimensional cartesian coordinate system whose origin corresponded to the transducer location. Computations involving both the translation and rotation of pixel coordinates of vessel wall contours were performed with commercially available mathematical software (PC MATLAB, The Mathworks, Inc, South Natick, Mass). The resulting three-dimensional matrices of pixel coordinates were next regrouped into sets based on their z coordinates along the axis corresponding to the catheter axis. Each set of coordinates was then used to generate a two-dimensional pixel image equivalent to the transverse section of the vessel wall contours. This resulted in a three-dimensional resolution—i.e., voxel element size —of 0.3×0.1×0.3 mm.

To improve the definition of vessel wall contours, interpolation was performed on the pixels in the previously generated
transverse section image. In addition, the region between the internal (lumen and wall border) and external wall boundaries was filled with solid pixels. Finally, the set of transverse section images was rendered into a volumetric display by use of a three-dimensional rendering software (SONOVIEW 2.5, Image-Comm) based on a voxel technique. The resulting display provided a clear depiction of lumen and wall anatomy, together with abnormalities in vascular geometry.

Validation Protocol

To compare data obtained by our 3DR, the following protocol was performed. The five arterial segments obtained at autopsy were processed as described above. Sections of the vascular segments were marked, and transverse histological slices were made at 0.2-cm distances from 0.5 to 1.5 cm distal to the position of the transducer indicated by the inserted pin on the artery. The specimens were dehydrated in graded alcohol and xylol and embedded in paraffin. Sections 4 μm thick were cut and stained with hematoxylin and eosin. After histological preparation, sections were photographed with a television camera and displayed on a Cine View Plus computer (Freeland Systems, Inc, Colorado Springs, Colo) for luminal area measurements. 3DR transverse slices comparable to the histological cuts were obtained, and lumen diameters and areas were measured by planimetry. Comparisons between 3DR and histology of lumen area and lumen diameter were performed.

Statistical Analysis

Linear regression analysis was used to compare matching data points. All data are presented as mean±SD.

Results

3DR was easily performed for all vascular segments. The reconstructions provided a clear depiction of lumen and wall anatomy, which could be viewed in any desired orientation and resliced in any orientation to allow further appreciation of the anatomic structure. Fig 4 is an example of the reconstruction of a canine aortic segment depicting wall and lumen. The proximal side of the aorta close to the transducer corresponds to a distance of approximately 1 cm from the transducer. Indentations and narrowing in the vessel wall depicted in the reconstruction were demonstrated on the original forward-viewing images and corresponding geometric alterations produced by our histological fixation technique.

A luminal reconstruction from a diseased human femoral arterial segment is depicted in Fig 5. Severe atherosclerotic vascular narrowing distally in the segment is shown. For more detailed analysis of luminal morphology, the segments can subsequently be resliced at set distances from the transducer and displayed. Fig 6 illustrates transverse sections from a canine aorta.
demonstrating alterations in wall and luminal morphology up to 2.6 cm (1.6 cm distal to the start of the reconstruction) from the transducer.

Fig 7A demonstrates comparisons of luminal areas by our 3DR technique versus histology. There was a good correlation between histology (Histo) and 3DR over the wide range of lumen area: $3DR = 1.5 \times \text{Histo}^{0.2}; r = 0.88$ (Histo luminal area range, 0.22 to 0.76 cm$^2$; 3DR luminal area range, 0.15 to 0.87 cm$^2$). The slope is close to unity and the intercept close to zero. Lumen diameter comparisons are illustrated in Fig 7B. Again, a good correlation between lumen diameters was obtained between 3DR and histology: $3DR = 1.4 \times \text{Histo}^{0.4}; r = 0.86$ (Histo luminal diameter range, 0.53 to 0.98 cm; 3DR luminal diameter range, 0.44 to 1.05 cm).

Discussion

We have demonstrated that 3DR of forward-viewing IVUS data is feasible and provides good definition of lumen and wall anatomy. Our discussion will focus on the benefits of this technique and comparison of our method with other methods of 3DR, factors influencing our results, and potential applications.

Benefits and Comparison With Other 3DR Methods

Forward-viewing IVUS catheters provide a unique imaging format not available with present side-viewing IVUS imaging devices. These catheters do not require placement across a critical lesion to detect atheroma mass and morphology.

Although two-dimensional IVUS imaging provides necessary anatomic vascular information, it is often not sufficient for detailed analysis of an entire lesion that is three-dimensional in nature. The use of 3DR techniques would overcome this problem by digitally integrating a set of two-dimensional images into a three-dimensional format.

To date, 3DR of IVUS images has been restricted to techniques that require recording of a sequence of transverse images during catheter pullback through a vascular segment.\textsuperscript{19,20} The inherent shortcoming of this technique, when carried out by a human operator, is the difficulty in maintaining a uniform pullback speed. An associated difficulty is the lack of in vivo position registration of the imaging transducer in these 3DR algorithms. The vascular segment may telescope during a pullback, resulting in misrepresentation of distances and anatomic geometry. As a result, because of limitations in accurately illustrating vascular morphology, 3DR of current IVUS image data may not always be quantitatively useful. With forward-viewing IVUS imaging, we have developed a 3DR technique that may overcome the above difficulties. In particular, since the placement of the forward-viewing IVUS catheter is fixed (except for axial rotation) throughout the imaging of a vascular segment, the need for position registration does not arise. Transverse sections derived from this 3DR technique are separated by a distance bounded by the axial resolution (0.1 mm with our 20-MHz prototype) of the forward-viewing IVUS images. This allows detailed analysis of lumen and wall, which is integral to the accurate assessment of the degree of atheroma and resultant stenosis.

Factors Influencing Results

For the purpose of demonstrating our 3DR method, a number of factors may have influenced the results of this study. Since the imaging data are in infancy, imaging and display are in nonstandardized modes. Therefore, full advantage of gray-scale range on the present forward-viewing images has not been maximally developed. The purpose of this article was to discuss the extension of forward-viewing data into a three-dimen-
sional format that would allow a complete evaluation of data from the forward-viewing catheter and the geometry of the segment distal to the catheter. Therefore, we have chosen to preprocess the forward-viewing images with manual contour tracing and display them without full gray scale. Real-time application of 3DR of forward-viewing IVUS images would require an automatic edge detection technique and/or a computer system capable of 3DR of a full range (0 to 256) of gray-scale images (as opposed to binary images). Both can potentially be done with presently available computer processing systems. Since the purpose of this study was to demonstrate the feasibility of 3DR of forward-viewing IVUS data, further work is required to allow automated edge detection to facilitate on-line 3DR. Methods of automatic edge detection of IVUS images such as those based on ultrasonic backscatter imaging or histogram analysis and thresholding might potentially be implemented into our 3DR algorithm.

One of the factors that might influence our 3DR method is the need to maintain a fixed axis of rotation during catheter imaging. This difficulty was circumvented in our study by the use of the precision mechanism on the microscope housing. For vascular beds in which segments are tortuous and a 1-to-1 rotation cannot be ensured between the transducer crystal and the distal shaft, a rotational encoder is necessary for accurate 3DR. For relatively short catheters and straight vascular segments (aorta, large peripheral arteries) in which a 1-to-1 rotation can be reasonably ensured, however, this 3DR method should allow accurate depiction of true vascular geometry in three-dimensional format.

The arterial specimens, although they varied from normal to atherosclerotic, were not perfusion fixed for the purposes of this study. Therefore, some irregularities in the geometry observed were a result of the histological preparation.

There are some potential limitations of 3DR with respect to present forward-viewing IVUS. These include limited depth of imaging field such that some large obstructions may not be fully imaged, lateral resolution of the imaging data, the requirement for linear correction of the present unstandardized image data with respect to distance from the catheter, and the effect of the incident acoustic angle on resolution of individual components of the arterial wall. As the forward-viewing ultrasound catheter development and imaging display improve, we anticipate that the full potential of 3DR of forward-viewing data and the importance of these theoretical limitations can be realized. However, our preliminary results are encouraging.

Potential Applications

In addition to providing the ability to determine detailed atherosclerotic vascular geometry without compromising the vascular lumen, a forward-viewing ultrasound device may have other applications. This device may allow prior lesion evaluation to better select an optimal interventional modality. Recently, a new direction has emerged in the design of interventional devices that integrate both angioplasty technology and IVUS imaging. An example is a combined ultrasound imaging–directional atherectomy device, in which ultrasound images are used to guide the extent of plaque removal. A forward-viewing IVUS device would allow directional imaging distally into the artery at intervention, possibly allowing full visualization of a lesion that had not yet been crossed. 3DR of such data with detailed regional slices at levels ahead of the catheter would provide a good road map for vascular anatomic depiction. Outside the vascular bed, 3DR of forward-viewing IVUS data may allow detailed analysis of small structures at laparoscopy (common bile duct, pancreatic ducts, fallopian tubes) without requiring direct cannulation of the structure.

Conclusions

These preliminary data demonstrate the feasibility of 3DR of forward-viewing IVUS data. This method may allow for rapid, detailed analysis of diseased arterial segments previously unavailable with standard IVUS and may permit more quantitative assessment of atheroma severity as well as better targeting of interventional procedures.

Acknowledgments

This study was supported in part by National Institutes of Health grant HL-46550, the Chicago Heart Association, and the Feinberg Cardiovascular Research Institute of Northwestern University. We wish to thank Jean Waller and Carolyn Johnson for their expert preparation of the manuscript.
References


Arterial imaging with a new forward-viewing intravascular ultrasound catheter, II.  
Three-dimensional reconstruction and display of data. 
K H Ng, J L Evans, M J Vonesh, S N Meyers, T A Mills, B J Kane, W N Aldrich, Y T Jang, P G Yock and M D Rold

Circulation. 1994;89:718-723  
doi: 10.1161/01.CIR.89.2.718

Circulation is published by the American Heart Association, 7272 Greenville Avenue, Dallas, TX 75231  
Copyright © 1994 American Heart Association, Inc. All rights reserved.  
Print ISSN: 0009-7322. Online ISSN: 1524-4539

The online version of this article, along with updated information and services, is located on the World Wide Web at:  
http://circ.ahajournals.org/content/89/2/718

Permissions: Requests for permissions to reproduce figures, tables, or portions of articles originally published in Circulation can be obtained via RightsLink, a service of the Copyright Clearance Center, not the Editorial Office. Once the online version of the published article for which permission is being requested is located, click Request Permissions in the middle column of the Web page under Services. Further information about this process is available in the Permissions and Rights Question and Answer document.

Reprints: Information about reprints can be found online at:  
http://www.lww.com/reprints

Subscriptions: Information about subscribing to Circulation is online at:  
http://circ.ahajournals.org/subscriptions/