True 3-Dimensional Reconstruction of Coronary Arteries in Patients by Fusion of Angiography and IVUS (ANGUS) and Its Quantitative Validation

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Background—True 3D reconstruction of coronary arteries in patients based on intravascular ultrasound (IVUS) may be achieved by fusing angiographic and IVUS information (ANGUS). The clinical applicability of ANGUS was tested, and its accuracy was evaluated quantitatively.

Methods and Results—In 16 patients who were investigated 6 months after stent implantation, a sheath-based catheter was used to acquire IVUS images during an R-wave–triggered, motorized stepped pullback. First, a single set of end-diastolic biplane angiographic images documented the 3D location of the catheter at the beginning of pullback. From this set, the 3D pullback trajectory was predicted. Second, contours of the lumen or stent obtained from IVUS were fused with the 3D trajectory. Third, the angular rotation of the reconstruction was optimized by quantitative matching of the silhouettes of the 3D reconstruction with the actual biplane images. Reconstructions were obtained in 12 patients. The number of pullback steps, which determines the pullback length, closely agreed with the reconstructed path length ($r=0.99$). Geometric measurements in silhouette images of the 3D reconstructions showed high correlation (0.84 to 0.97) with corresponding measurements in the actual biplane angiographic images.

Conclusions—With ANGUS, 3D reconstructions of coronary arteries can be successfully and accurately obtained in the majority of patients. (Circulation. 2000;102:511-516.)

Key Words: arteries ▪ ultrasonics ▪ angiography

Intravascular ultrasound (IVUS) generates images with a high temporal and spatial resolution1,2 and is useful to evaluate both vessel wall morphology and dimensions before and after catheter-based interventional procedures.3 However, IVUS imaging is a tomographic technique, which makes it difficult to grasp an overview of an investigated vessel segment. To partly overcome this limitation, multiple images can be acquired during a catheter pullback. Assuming a straight pullback trajectory, 3D stacking of these images is simple and provides a useful overview of the IVUS information.4–6 More realistic 3D reconstruction methods have been devised that take into account the curved path of the transducer during pullback.7,8 These methods reconstructed the 3D path from multiple biplane x-ray recordings of successive transducer locations8 or used the vessel centerline as an approximation.7 However, some important reconstruction problems related to determination of the true orientation of the IVUS cross sections and susceptibility to respiratory motion remained to be solved.

We developed a true 3D reconstruction method called ANGUS9,10 (fusion of angiography and IVUS) to solve these problems. The applicability of this reconstruction method was evaluated in 16 patients, and the accuracy of the reconstructions obtained was determined quantitatively.

Methods

Basics of True 3D Reconstruction

Before describing the ANGUS method in more detail, in this section we briefly present the basic steps required for true 3D reconstruction of an artery from IVUS and biplane information. In the heart catheterization laboratory, a 3D coordinate system was defined by recording a calibration cube for a certain biplane geometry (Figure 1A). When a single marker is imaged with this calibrated geometry, its 3D position can be reconstructed from its location on the biplane images.11

Received December 1, 1999; revision received February 25, 2000; accepted February 29, 2000.


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position itself (Figure 2C), and we therefore use the 3D reconstructed catheter as a "backbone" for the vessel reconstruction. This reduces susceptibility to respiratory motion. Acquiring the IVUS images in an R-wave–triggered mode reduces the effect of cardiac motion.

Repositioning an IVUS cross section on the reconstructed trajectory involves 3 distinct steps. First, the transducer locations on the trajectory need to be reconstructed. Second, the center of the IVUS image is positioned at a reconstructed transducer location, and the imaging plane is oriented perpendicular to the trajectory. Third, the IVUS image needs to be rotated around the trajectory (Figure 2D and 2E) to achieve a true reconstruction. Considering the orientation of intimal thickening, the rotation shown in Figure 2D corresponds better with Figure 2C than 2E.

In Vitro Models
As a first model, to validate catheter reconstruction, a metal wire (diameter 0.5 mm, length 100 mm) with 11 radiopaque markers attached at 10-mm intervals, was bent in a helical turn (radius 35 mm, pitch 65 mm).

A second model allowed angiographic and IVUS lumen imaging. On the surface of a 120-mm-diameter plastic cylinder, a gutter (width and depth 3 mm) was machined in a helical course (pitch 100 mm). The gutter was watertight, closed by a flat strip. Consequently, gutter cross sections had a flat side aligned to the cylinder surface.

Patient Study
To test the applicability and accuracy of ANGUS in the clinical setting, 16 patients who gave informed consent were investigated 6 months after implantation of a Wallstent in a study that was approved by the institutional medical ethics committee. The vessels studied in these patients were the left anterior descending (LAD, n=6), right (RCA, n=9), and left circumflex (LCx, n=1) coronary arteries.

Acquisition of X-Ray Images
After the IVUS pullback was begun, biplane x-ray filming at 25 frames per second (BICOR, Siemens AG) recorded the position of the catheter. Simultaneously, an angiogram was made by manual injection of radiopaque dye (Iopamiro 379, Bracco, 2:1 vol/vol diluted with saline) through the guiding catheter (8F). The use of diluted contrast allowed simultaneous visualization of the IVUS catheter and the lumen. For calibration of the x-ray geometrical settings, the calibration cube and a flat calibration grid were filmed after the procedure. The grid was filmed against the entrance screens of the image intensifiers and allowed calibration at this level of the imaging chain. Films were stored in DICOM format (8 bits, 512×512 pixels) on a compact disk.

For synchronization purposes, the data acquisition system ACODAS (DATAQ Instruments Inc) recorded the x-ray pulses.

Acquisition of IVUS Images
For IVUS imaging, a 2.9F sheath-based catheter (MicroView, CVIS) was used. This catheter has an ultrasound-transparent distal sheath that contains either the guidewire (during catheter introduction) or the rotating imaging core. Imaging is applied at 30 MHz with the core rotating at 1800 rpm.

Images were acquired at the top of the R wave of the ECG after detection of a regular R-R interval. Then, the catheter was pulled back by 0.5 mm with a stepping motor. The ECG and stepping pulses were recorded by ACODAS for synchronization purposes. IVUS images were digitally stored (8 bits, 256×256 pixels) in a personal computer. In parallel, a continuous VHS tape recording also was made of all IVUS images.

Processing of X-Ray Images
From the x-ray recordings, a biplane set of end-diastolic frames was selected, optimally showing the catheter and the contrast-filled lumen. These frames were stored in a personal computer and first used to define the catheter centerline (coreline) from its radiopaque tip (distal) to its intersection with the guiding catheter entrance (proximal, Figure 1B and 1C). Second, the borders of lumen and stent were determined. For contour determination, custom-made software was used, incorporating standard zooming and contrast optimization features to aid recognition of image details. No borders were indicated near side branches or unopacified areas. In the calibration images, the edges of the calibration cube and a 5×5-cm area of the grid were indicated.

Processing of Ultrasound Images
To determine lumen and stent borders in the IVUS images, a semiautomatic contour detection program was used, which was guided by operator corrections. At this stage, display of the continuous IVUS tape recording greatly aided the operator in border recognition.

The contours obtained are described in polar coordinates with the catheter as origin and the radius to the contour points as a function of the angle. For each cross section, this radial function is converted into the Fourier domain, calculating 16 harmonic terms. The Fourier coefficients obtained are arranged in matrix notation, and by use of the fast Fourier transform (MATLAB, MathWorks), a continuous 2D Fourier description of the whole vessel is obtained. By removal of
the highest half of axial frequency components, smoothing is obtained, which greatly eliminates axial diameter variations occurring within 1 mm.

Reconstruction of the Catheter Centerline (Coreline)
The method to reconstruct a single point in 3D space from its biplane projections was introduced by McKay and has been adapted by many investigators. To determine the required mathematical descriptions, at least 6 noncoplanar 3D calibration points are needed. We used the 8 corner points of the calibration cube, extrapolating these from the cube edges.

3D reconstruction of the coreline requires a quite different approach. Only the proximal and distal end points of the coreline can be directly reconstructed in 3D. Between these points, a 3D circular segment is defined that serves as a first coreline approximation. Next, this segment is stepwise adapted in 3D until its computed biplane projections optimally match with the actual drawings of the coreline. To quantify matching, 128 points are defined on the 3D coreline. Their computed biplane projections are compared with 128 corresponding points assigned to each of the coreline drawings (for details, see Appendix), and root-mean-square (RMS) distance between corresponding points quantifies matching quality.

The 3D length of the reconstructed coreline, minus a fixed 8.5 mm (distance from tip to transducer), is compared with the pullback distance from distal to proximal.

Location and Orientation of the IVUS Planes
The locations of the IVUS cross sections are distributed at equidistant intervals on the reconstructed coreline. The imaging planes are positioned perpendicular to the coreline, and then the angular rotation (Figure 2D and 2E) is determined as follows.

First, an arbitrary rotation for the distal IVUS image is chosen, and the rotation of each consecutive plane is derived by a discrete implementation of the Frenet rules. This algorithm corrects for a twist-like phenomenon that induces a rotation of the IVUS images when the catheter passes through helical curves. Second, biplane silhouette images of the lumen or stent surface reconstruction are computed and quantitatively compared with the actual x-ray images. In Figure 3, an example is given of a reconstructed stent (shown as a tube) for 2 different rotations. In the stent angiogram, distances (examples d, d) between catheter coreline and stent border are measured at corresponding locations. Obviously, best correspondence exists between angiogram and 270° reconstruction.

Diameter Measurements
Summation of adjacent distances yields local lumen and stent diameters. If both biplane views are combined, a maximum of 120 diameter measurements can be obtained.

Statistics
Data are summarized as mean±SD. Distances and diameters from the actual x-ray images and from the 3D reconstruction–derived silhouettes were compared by linear orthogonal regression, and the SEE was calculated.

Results
Wire Model
The reconstructed coreline length was 99.7 mm, close to the actual 100-mm wire length. The computed coreline 3D projections closely resembled the actual wire centerlines, because RMS distance between corresponding points was only 0.57 mm (n=256).
By the single-point 3D reconstruction method, the 11 marker locations could be reconstructed in 3D. Comparing these locations in 3D with those of 11 corresponding points distributed at equal distances on the reconstructed coreline showed an RMS distance of only 0.61±0.36 mm.

Gutter Model
Length of the reconstructed 3D coreline was 108.5 mm, close to the derived pullback distance of 106.5 mm. The computed coreline projections fitted accurately with the actual drawn corelines, because RMS distance between both curves was only 0.26 mm (n=256).

The distances from coreline to lumen border (n=178) in the angiogram correlated best with those from the computed gutter silhouettes at 80° angular rotation (r²=0.86). A similar comparison between diameters at 80° yielded Dsilh=1.06 Danio−0.06 mm (r²=0.90, n=73). Figure 5B and 5C presents rendered views of the reconstructed gutter.

Patient Artery Reconstructions
Reconstructions of arteries and stents were successfully obtained in 12 patients (7 RCA, 4 LAD, and 1 LCx), with the stent contours used to determine angular rotation. Figure 6 shows a rendered view of an RCA reconstruction. In 4 patients (2 LAD, 2 RCA), poor x-ray image quality, too much foreshortening, or calibration error precluded reconstruction.

Length (Lcore) of the 12 reconstructed corelines ranged from 36 to 76 mm. Comparing these with the number of pullback steps (n), which represent the actual length, yielded Lcore=0.48 n+4.1 mm (r=0.99).

The computed 3D coreline projections matched accurately with the actual corelines, because the residual RMS distances varied from 0.1 to 1.6 mm (0.65±0.46 mm).

Determination of angular rotation by use of the lumen for matching succeeded in 7 of the 12 patients. The absolute difference between stent- and lumen-determined rotations was only 17±12°; the mean of the signed differences was 6°.

At optimal rotation, determined on the basis of stent matching, the 12 individual distance relations showed correlation coefficients ranging from 0.84 to 0.97 (0.91±0.04). With the lumen, the average correlation of the distance relations was 0.84±0.12 (n=7).

Combining all in-stent distance measurements for the 12 patients in an orthogonal linear regression analysis yielded dsilh=0.90 danio+0.19 mm (n=2344, r=0.92, SEE=0.17 mm), with dsilh the distance in the computed reconstruction silhouette and danio the corresponding distance in the actual stent angiogram (Figure 7).

A similar comparison between all stent diameters (D) in the 12 patients yielded Dsilh=1.02 Danio−0.06 mm (n=1106, r=0.92, SEE=0.19 mm) (Figure 7).

Discussion
Coronary 3D Reconstruction
Several investigators16,17 used coronary biplane angiograms for 3D reconstruction of the coronary skeleton and/or lumen. However, such lumen reconstructions require assumptions
about the shape of the lumen cross sections and therefore have limited applicability. The combined use of high-resolution IVUS imaging and biplane angiography offers an attractive alternative for 3D coronary artery reconstruction. In particular, the possibility to reconstruct the arterial wall is of great value, because this allows new in vivo studies relating spatial wall characteristics with hemodynamic parameters derived from computational fluid dynamics applied to the lumen reconstructions.18

In this study, we report on our current ANGUS method and its clinical validation. The added quantitative comparison between the silhouettes of the 3D reconstructions and the actual x-ray images allows determination of the angular rotation of the IVUS images9 in an objective way. Furthermore, this method allows quantification of the quality of the 3D reconstruction. ANGUS appears to be able to 3D-reconstruct stents and coronary arteries in the majority of investigated patients with high accuracy.

Coreline Reconstruction
In this study, we used a calibration cube to determine the transformation matrices11 required for 3D reconstruction, because this method was more accurate than using the x-ray geometry data available on line.9

Reconstruction of the 3D coreline by the parameter-fitting approach (Appendix) worked successfully and with high accuracy. Part of the remaining distance error may originate from remaining cardiac and/or respiratory motion, because the alternating acquisition of the different biplane images differed by 20 ms. Therefore, these images did not present exactly the same 3D catheter position.

The helical wire model allowed an interesting comparison in 3D space of the location of reconstructed points on the coreline with the actual single-point reconstructed markers. The spatial error was very small and indicates that for this model, good matching in the 2D projection images was paralleled by an accurate spatial coreline reconstruction.

The reconstructed pullback length in the gutter model and in the patients slightly exceeded the length derived from the number of pullback steps. Some difficulty occurred in estimating the proximal intersection of the coreline with the guiding catheter because of a diminished radiopacity of the soft tip of the guiding catheter. The distal tip position could be accurately indicated and was used rather than the IVUS transducer because of its better visibility.

Stent and Angiographic Matching
In this study, we derived the angular rotation on the basis of matching with the stent and with the lumen. Because the contrast agent slightly impaired recognition of the stents, this may have decreased the success rate of matching on the basis of the stent. Similarly, visualization of the lumen was partially hampered by the stent, which prohibited use of this part for lumen matching. Future studies using lumen matching without interference of visible stent structures probably will show a higher success rate.

The angular rotations determined from both the lumen and stent matching procedures agreed closely. This important result demonstrated that the applied IVUS catheter had a high angular accuracy, because the matching structures of the stent and the angiographic borders were at different segments in the arteries investigated. Therefore, if we avoid the reconstruction of vessels with tight stenoses, in which catheter friction may induce rotational error, angular rotation can be accurately reconstructed by any of the methods.

In this study, we generally used the catheter position relative to the lumen or stent border in the silhouette images (distances) to determine angular rotation. The diameters of a stent are unsuited for this purpose, because the circular cross sections are invariant for angular rotation. Indeed, distances may not change by rotation either if the catheter passes through the center of a stent. Obviously, this situation will rarely occur. When lumen matching is applied, the diameters may serve well (see for example the gutter results), because the lumen silhouettes are more dependent on angular rotation.

Comparing IVUS and X-Ray Measurements
We used orthogonal regression analysis because this method is independent of the choice of IVUS or angiography as the independent variable. The excellent result of the combined distance comparison (Figure 7) proved that the catheter sheath position at the beginning of pullback indeed accurately predicted the pullback trajectory. Apparently, the successive positions of the transducer in the IVUS images relative to the stent borders corresponded well with that shown by the actual catheter biplane images. The residual differences, derived from the regression equation, were only 0.12 mm for the smallest (0.6 mm) and ~0.12 mm for the largest (3 mm) distances. Probably, the sheath position is so stable because the sheath continuously strives to maintain a position at minimal bending energy. This condition is almost insensitive to the insertion depth of the imaging core, because this has a much higher flexibility than the sheath. We did not use the lumen data to test the stability of the sheath. Then, increased noise may be expected from a possible change of state in vasomotion during pullback and from the less well-defined lumen borders for both imaging modalities.

The values for slope (1.02) and intercept (~0.06 mm) of the stent-diameter relation (Figure 7) between the reconstruction silhouettes and the actual angiograms indicate that no important calibration errors existed in the IVUS or in the biplane imaging system. The small negative intercept (~1
stent wire diameter) may originate from the different indications of the stent borders in the IVUS and in the angiographic images. The observed random error originates from uncertainties in the angiographic and IVUS border determination and from digitization noise. Differences in determining the corresponding measurement locations will also exist.

Limitations
A limitation in application of the method is the fact that the acquisition setup requires biplane imaging, a sheath-based catheter type, and a motorized stepped pullback device. In addition, the current inability to incorporate side branches in the reconstruction does not allow complete vessel reconstruction.

Conclusions
3D reconstruction of coronary arteries by ANGUS can be applied in clinical practice with a high rate of success and with high accuracy, because the path followed by a sheath-based IVUS catheter can be predicted with high accuracy from a single set of biplane angiographic images. Both location and angular rotation of IVUS images can be accurately derived from a quantitative comparison of the 3D reconstruction silhouette with the angiogram. This comparison also allows quantification of the quality of the reconstruction. IVUS-derived Wallstent diameters as measured in the 3D reconstruction silhouette equal those derived from the angiogram.

Appendix
The searched 3D coreline is described as a series of points aligned along a curve. The present description differs slightly from that used previously. For \( n = 0, 1/127, 2/127, \ldots, 1 \), a total of 128 vector points \( \mathbf{P}(n) \) are defined: \( \mathbf{P}(n) = A + nB + C \sin \phi_0 + D \cos \phi_0 + E \sin 2 \phi_0 + F \cos 2 \phi_0 + G \sin 3 \phi_0 + H \cos 3 \phi_0 \).

The angle \( \phi_0 \) and vectors \( A, B, C, \ldots, H \) have to be determined. The terms \( C \sin \phi_0 \) and \( D \cos \phi_0 \) describe a segment of an elliptical curve. The angle \( \phi_0 \) determines the extent of this segment; for \( \phi_0 = 360^\circ \), a full ellipse is described. Vector \( A \) is a displacement vector. Vector \( nC \) adds pitch to allow description of helical curves. The terms preceded by \( E, F, G, \) and \( H \) describe higher-order details.

For a first approximation of \( A, C, D, \) and \( \phi_0 \) (other coefficients set to zero), a circular segment is computed, passing through the distal and proximal end points of the coreline and a third 3D point reconstructed from a point selected at the middle of each of the coreline drawings. For matching, the biplane projections of the 128 curve points are computed and compared with 128 points assigned to the actual 2D corelines. The latter points are defined on the corelines at relative distances similar to those of the projected curve points. The RMS value of distances between corresponding points provides a cost function, which is minimized by adjustment of the unknowns with a Gauss-Newton iterative solver (MATLAB). After \( A, C, D, \) and \( \phi_0 \) are first adjusted, other unknowns are stepwise added and optimized.

Acknowledgments
The contribution of the catheterization laboratory technicians and nurses in improving and implementing the protocol is gratefully acknowledged. The authors thank Andrew Tjon and Harry Achterberg for their contribution in implementing and improving the analysis procedures.

References
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_Circulation_. 2000;102:511-516
doi: 10.1161/01.CIR.102.5.511

_Circulation_ is published by the American Heart Association, 7272 Greenville Avenue, Dallas, TX 75231
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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/102/5/511

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