Usefulness of On-Line Three-Dimensional Reconstruction of Intracoronary Ultrasound for Guidance of Stent Deployment

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The additional information provided by automated on-line 3-dimensional (3-D) reconstruction of intracoronary ultrasound (ICUS) was assessed in 42 patients (62 stents) who underwent stent deployment after achieving an optimal quantitative angiographic result. In 10 of 42 patients, 3-D ICUS was also performed before stenting. ICUS images of stents and adjacent reference segments were acquired by using a motorized pullback at a constant speed (1 mm/s) and immediately processed in the catheterization laboratory. Optimal stent expansion was detected by 3-D ICUS in case of complete apposition of stent struts to the vessel wall. Furthermore, an attempt was made to maximize the intrastent lumen area to match lumen area of the reference segment and to cover with stents all the segments with residual significant lesions (plaque burden >50%). Three-dimensional automated reconstruction of ICUS was successful in 8 of 10 patients (80%) before, and in 36 of 42 patients (86%) after stent deployment. In all 8 patients who underwent successful 3-D ICUS assessment before stent implantation, the selection of stent length was facilitated by accurately measuring the lesion length. After stenting, 3-D ICUS modified the management strategy in 21 of 36 patients (58%), triggering additional high-pressure dilatations in 13 patients (36%) and additional stent deployment in 8 (22%). In conclusion, on-line 3-D ICUS facilitates stent selection and strongly modifies the revascularization strategy by accurately detecting stent underexpansion and presence of uncovered lesions. (Am J Cardiol 1996;77:455–461)

Recent studies have documented that the use of intracoronary ultrasound (ICUS) for guidance of stent deployment allows an optimization of stent expansion that translates into 2 major clinical benefits: a large reduction in the incidence of subacute stent thrombosis and a decrease in the restenosis rate. The current technique requires a cumbersome and subjective review of the ICUS examination at each step of the procedure, selecting and measuring the minimal cross-sectional area within the stented segment and 2 appropriate reference cross-sectional areas proximal and distal to the stent. A recently developed on-line 3-dimensional (3-D) reconstruction system can facilitate stenting guidance by providing a longitudinal display of the entire length of the stented segment and of the adjacent reference segments. In this study, the clinical usefulness of 3-D ICUS was assessed in 42 patients undergoing stent deployment.

METHODS

Patient group: From June 1994 to February 1995, 3-D ICUS imaging was performed in 42 patients (62 stents) who underwent stent deployment. Thirty-one patients (74%) were men and 11 (26%) were women (mean age 59 ± 7 years). Data on patients and procedures are listed in Table I.

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Procedure: After stent release or initial deployment, additional dilatations in the stented segment were performed with balloons up to 0.5 mm greater than the interpolated reference diameter until a negative percent diameter stenosis was obtained by quantitative coronary angiography (QCA) (minimal lumen diameter within the stent larger than the reference diameter).

After a quantitative coronary angiographic criterion indicative of optimal stent expansion was met and the procedure was considered complete, 3-D ICUS was performed. To assess the impact of 3-D ICUS on subsequent revascularization strategy, the treatment strategies planned before and after 3-D ICUS were compared. In a group of 10 patients (24%), 3-D ICUS was also successfully performed before stenting and its results were used to plan the subsequent stent selection. No complications due to the insertion of the ICUS catheter occurred.

All patients received 250 mg of acetylsalicylic acid. A bolus dose of 10,000 IU of heparin was administered during the procedure and repeated if necessary in order to maintain an activated clotting time of >300 seconds. Oral anticoagulants were started the day of stent implantation and administered for ≥ 3 months at a dose sufficient to maintain the thrombin time between 5% and 10%.

Quantitative coronary angiography: The angiographic analysis was performed on-line with a computer-assisted system using an automated edge-detection algorithm (CAAS II, Cardiovascular Angiography Analysis System II, Pie Medical Data, Maastricht, and ACA, Philips DCL, Eindhoven, The Netherlands).7 The treat-
TABLE I Clinical, Angiographic, and Procedural Data

<table>
<thead>
<tr>
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<th>Number of Patients (%)</th>
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<tr>
<td>Patients</td>
<td>42</td>
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<tr>
<td>Coronary artery</td>
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<tr>
<td>Left anterior descending</td>
<td>23 (55)</td>
</tr>
<tr>
<td>Left circumflex</td>
<td>3 (7)</td>
</tr>
<tr>
<td>Right coronary</td>
<td>16 (38)</td>
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<tr>
<td>De novo lesion</td>
<td>30 (71)</td>
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<tr>
<td>Restenosis</td>
<td>12 (29)</td>
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<tr>
<td>Elective procedure</td>
<td>31 (74)</td>
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<tr>
<td>Bailout procedure</td>
<td>11 (26)</td>
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<tr>
<td>Single stent</td>
<td>29 (69)</td>
</tr>
<tr>
<td>Multiple stent</td>
<td>13 (31)</td>
</tr>
<tr>
<td>Inflation pressure (atm)</td>
<td>14 ± 3</td>
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<tr>
<td>Balloon diameter (mm)</td>
<td>3.6 ± 0.5</td>
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<tr>
<td>Number of stents</td>
<td>62</td>
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<tr>
<td>Stents/patient</td>
<td>1.5</td>
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<tr>
<td>Stent type (n = 62)</td>
<td></td>
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<tr>
<td>Palmaz-Schatz*</td>
<td>31 (50)</td>
</tr>
<tr>
<td>Wallstent+</td>
<td>14 (23)</td>
</tr>
<tr>
<td>Cordis</td>
<td>7 (11)</td>
</tr>
<tr>
<td>Microstent</td>
<td>6 (10)</td>
</tr>
<tr>
<td>Gianturco-Roubin</td>
<td>2 (3)</td>
</tr>
<tr>
<td>Multilink</td>
<td>2 (3)</td>
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+Schneider, Zurich, Switzerland.
©Cardis Corporation, Miami, Florida.
®Applied Vascular Engineering, Edmonton, Canada.
≤Cook, Inc., Bloomington, Indiana.
*Advanced Cardiovascular Systems, Inc., Temecula, California.

Three-dimensional intravascular ultrasound: Vessels were imaged with a mechanical 2.9Fr (diameter 0.96 mm) ultrasound catheter (Micro-View 30 MHz, Cvis, Sunnyvale, California). The imaging probe was positioned distal to the lesion and withdrawn at a constant speed of 1.0 mm/s by using a motorized pullback device. On-line 3-D reconstruction was performed with a system processing ICUS images with an algorithm based on acoustic quantification of blood and coronary wall backscatter (EchoQuant, Indec System, Inc., Capitola, California). The method has been previously validated in an animal model and has been already described in detail.9,10 The program runs on a dedicated Intel Pentium 60 MHz PC with an OS2 operating system and uses a digitization frame rate of 8.5 images/s. The system was analyzed using a single optimal projection (working projection) and after intracoronary injection of 1 to 3 mg of isosorbide dinitrate. Because automated detection of an interpolated reference diameter is unreliable after stent implantation, percent diameter stenosis was calculated as the ratio of stent minimal lumen diameter and a user-defined reference lumen diameter, measured in an angiographically normal unstented proximal or distal segment. At the end of the procedure, quantitative coronary angiographic analysis was limited to the stented segment in order to detect focal segments of uneven or incomplete stent expansion.

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acquires 255 transverse views in 30 seconds, and after an additional processing time of 125 seconds, it displays the reconstructed 3-D image and the quantitative analysis of the studied segment (30 mm long at a pullback speed of 1 mm/s).

Immediate information on the adequacy of stent deployment can be obtained by the longitudinal view of the analyzed segment and by a diagram showing the automatic measurements of minimal lumen diameter and of minimal lumen area along the reconstructed segment. Automatically contoured cross-sectional areas are easily selected by scrolling the longitudinal view of the measurement diagram with a cursor. With this approach, the minimal lumen cross-sectional area within the stent and 2 reference proximal and distal frames in undiseased segments can be selected. The automated contour detection of minimal stent lumen area and of the reference areas can be corrected manually in case of failure of the automatic analysis algorithm. Furthermore, it is possible to manually trace the external contour of the total vessel area, defined as the interface between plaque-media complex and adventitia. Plaque burden can be calculated as the difference between total vessel area and lumen area. A 3-D cylindrical format is also available and displayed as a "clamshell" view, with the vessel open longitudinally and both halves tilted back 30°, showing the inner surface of the vessel (Figures 1 and 2).

Based on the result of the 3-D ICUS evaluation, additional high-pressure balloon dilatations inside the stent were performed in case of incomplete apposition of the stent struts to the vessel wall or an asymmetric stent expansion of the stent with a minimal to maximal lumen diameter ratio <0.7. Furthermore, the intrastent lumen area was increased up to a level matching the average lumen area of the proximal and distal reference segments. The percent area stenosis within the stent was calculated using the following equation: intrastent percent area stenosis = [(1 - stent minimal lumen area)/average lumen area of proximal and distal references] × 100. Additionally, all segments with significant atherosclerotic involvement (plaque area >50% of the total vessel area) were covered with stents.

**Data analysis:** All continuous variables were expressed as mean ± SD. Continuous variables were compared with paired 2-tailed Student’s t test, whereas non-parametric tests were used for discrete variables. A p value <0.05 was considered statistically significant.

**RESULTS**

**Feasibility:** Three-dimensional automated reconstruction of intravascular ultrasound offered valuable information on adequacy of stent deployment and vessel architecture in 36 of 42 patients (86%) after stent deployment and in 8 of 10 patients (80%) before stenting. In

![Image](image-url)

**FIGURE 2.** Lower panel, longitudinal view showing abrupt vessel tapering distal to a side branch. However, the corresponding transverse view (upper left panel) excludes the presence of a significant atherosclerotic encroachment as the cause of lumen reduction. Abbreviations as in Figure 1.

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all, unsuccessful on-line 3-D reconstructions occurred in 8 patients. In 5 patients, unsuccessful 3-D reconstructions were mainly due to failure of the algorithm used for lumen detection due to the presence of shadowing of extensive calcium deposits interpreted as lumen. In 3 patients, failure occurred because of side branches and lack of sharpness of the lumen wall interface, partially caused by the non coaxial position of the ultrasound catheter inside the lumen.

Three-dimensional intravascular ultrasound assessment of lesions before stent implantation and related impact on revascularization strategy: In all 8 patients who underwent successful 3-D ICUS assessment before stent implantation, complementary information on the angiographic measurements of lesion length was obtained. The selection of the stent length was facilitated by measuring lesion length and distance between stenosis and vessel ostium or origin of major side branches. In 2 of 8 patients (25%), an additional significant lesion (plaque burden >50%) was revealed by 3-D ICUS and additional stents were placed (Figure 3).

Three-dimensional intravascular ultrasound assessment of adequate stent expansion and related impact on revascularization strategy: QCA and 3-D ICUS measurements were compared after an optimal angiographic result was obtained. The stent minimal lumen diameter was significantly overestimated by QCA compared with 3-D ICUS (3.0 ± 0.4 vs 2.7 ± 0.4 mm, respectively, p <0.01). The percent area stenosis within the stent was significantly greater by 3-D ICUS than by QCA (24 ± 16% vs −7 ± 11%, respectively, p <0.01). Strut protrusion within the vessel lumen and/or asymmetric stent expansion caused by a large eccentric underlying plaque was seen in 3 of 36 patients (8%) (Figures 4 and 5). Three-dimensional ICUS triggered further high-pressure balloon dilatations within the stent in 13 patients (36%) to correct asymmetric stent expansion or increase the intrastent lumen area. A residual plaque burden >50% in the segments adjacent to stent endings was found by 3-D ICUS evaluation in 8 patients (22%). In all 8 patients, the uncovered diseased segments were treated with additional stent implantations. On the whole, after stenting, the management strategy was modified in 21 of 36 patients (58%).

Clinical outcome: Subacute stent thrombosis occurred in 1 patient after implantation of a Gianturco-Roubin stent in the left anterior descending artery as a bailout procedure for acute vessel occlusion. The initial result was not satisfactory with ICUS and angiography despite the use of a second overlapping Gianturco-Roubin and multiple high-pressure dilatations.

FIGURE 3. Three-dimensional reconstruction obtained after positioning of a 15 mm long Palmaz-Schatz stent in the mid-left anterior descending artery clearly shows a large residual plaque proximal to the stent. The longitudinal view in the lower panel shows the residual plaque, indicated by a vertical line and starting immediately after the takeoff of a large diagonal branch (arrowhead). The presence of a residual plaque is also documented by the corresponding transverse view (upper left), and by the measurement diagram (upper right) showing a reduction in lumen area due to plaque protrusion. MLD = minimal lumen diameter.
DISCUSSION

In this study, we assessed the possibility to guide stent implantation with on-line 3-D reconstruction of ICUS. Angiography gives information only on vessel lumen dimensions and has limitations for the measurement of lesion length. ICUS permits direct visualization of plaque characteristics and dimensions, and can reveal significant stenoses that were not suspected angiographically.

For this reason, the use of ICUS has been proposed for guidance of interventional procedures. In particular, these investigators, who acquired great experience in the application of ICUS before coronary interventions, reported a modification of the overall revascularization strategy in 40% of patients after ICUS assessment.

In this study, 3-D ICUS evaluation before stenting was rarely performed but altered the treatment strategy in 2 of 8 patients (25%) in which 2 additional significant lesions, underestimated by QCA, were stented.

Three-dimensional ICUS can also support the decision to avoid revascularizations planned on quantitative coronary angiographic evaluations. In a recent report by Mintz et al on ICUS assessment of ambiguous and intermediate angiographic lesions, planned revascularizations were aborted in a high percentage of patients, and only 10% of these patients required target lesion revascularization at a 1-year follow-up.

Three-dimensional ICUS also provides an accurate evaluation of lesion length and distance between lesion and coronary ostium or large side branches, obviating the risk of angiographic vessel foreshortening. A proper definition of longitudinal vessel architecture is a valuable prerequisite for an appropriate stent selection and facilitates stent deployment.

Further trials are needed to clarify whether ICUS guidance of stent deployment is required in all cases to reduce subacute thrombosis and late restenosis. However, for an ICUS-guided application, the use of 3-D reconstruction after stenting offers advantages over the conventional ICUS assessment since the on-line longitudinal view of the entire stent length and of the adjacent segments provides a quick overview of the adequacy of stent deployment and of the unstented vessel architecture.

Furthermore, stent underexpansion is evaluated more accurately and objectively by 3-D than by 2-D ICUS because the combined use of a longitudinal display and of a measurement diagram leads to a precise evaluation of the stent minimal lumen cross-sectional area. In a previous report on the comparison between 2-D and 3-D ICUS assessment of stent deployment, 3-D ICUS was more sensitive in evaluating inadequate stent expansion.

The high success rate of automated 3-D reconstruction before and after stenting shows that the technique is feasible for guidance of stent implantation. The few cases of unsuccessful 3-D reconstruction were mainly due to insufficient quality of acquired ICUS cross sections. In particular, presence of side branches or a suboptimal setting of the time-gain compensation may deter-

![Figure 4](https://example.com/figure4.png)

**Figure 4.** Upper left panel, transverse view of the distal Palmaz-Schatz stent showing an incomplete stent expansion with >50% residual cross-sectional area stenosis (CSA St.) due to severe eccentric plaque. Left lower panel, a transverse view obtained in the same position showing a larger and more circular lumen area after additional high-pressure balloon dilations. Right panels, corresponding measurement diagrams with the lumen area and lumen diameter along the reconstructed segment are displayed. **MLD** = minimal lumen diameter.
mine an inaccurate delineation of the intimal border which hampers the quality of 3-D reconstruction. Additionally, shadowing caused by calcium deposits can be inappropriately interpreted as lumen by the blood speckle identification algorithm which is not based on geometric assumptions. The development of ICUS imaging with higher resolution and the use of a different method of acquisition of ICUS images based on electrocardiographic triggering, minimizing motion artefacts derived from the heart cycle, should further increase the success rate of automated 3-D reconstruction.

In this study, subacute stent thrombosis occurred only in 1 patient (2%) whose immediate result was grossly unsuccessful because of plaque protrusion within 2 overlapping coil stents.

**Study limitations:** Because there is no clear consensus on the ICUS criteria of adequate stent expansion to be used, in this study a residual area stenosis within the stent was accepted in most cases.

Some factors can interfere with a correct acquisition of the sequence of ICUS images and limit the quality of 3-D reconstruction. In particular, curvatures of the vessel induce a distortion of the 3-D image, which is reconstructed along a straight line through the center of successive cross sections.

Because the acquisition of ICUS images was not based on electrocardiogram triggering, the accuracy of quantitative measurements was limited by systolic expansion of the coronary vessel and the movement artefact of the ultrasound catheter.11,24
