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Editorial Comment

Intravascular Ultrasound

A Fantastic Voyage

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In the 1966 film "Fantastic Voyage," Raquel Welch and her compatriots are electronically miniaturized and travel through the bloodstream on an incredible journey where they see heart valves and obstructions in the arterial circulation. Like a Jules Verne science fiction prediction that later was realized, it is now feasible to image the venous and arterial circulation from inside the vessel with a 1.0-mm ultrasound transducer catheter. The latest advance in this odyssey is the ability to reconstruct a three-dimensional representation of a human coronary artery in vivo. This editorial will attempt to put into perspective the study on three-dimensional reconstruction of intravascular ultrasound images presented by Rosenfield et al[1] in this issue of *Circulation.*

See p 1938

The driving force behind the development of intravascular ultrasound is the need for more complete information about the atherosclerotic plaque during percutaneous interventions. Despite the enormous advantages of angiography, the information that it provides is limited to a "lumenogram," that is, a two-dimensional representation of a more complex three-dimensional structure. Any conclusions about the extent of the atheroma is derived by inference as the plaque encroaches upon the lumen. The plaque itself is not visualized by angiography. The depth of the atheroma is unknown, and limited information is available about the composition of the tissue within the plaque. The result of these deficiencies is that angiography underestimates the extent of atherosclerotic disease.

The observations made with intravascular ultrasound imaging can be grouped into the following categories: morphological information, tissue composition of the plaque, and pathophysiological observations after coronary interventions. The most striking impression from intracoronary images is that the extent of atherosclerosis present within the wall of the artery is much greater than one imagines from the angiogram. Intravascular imaging permits for the first time in vivo visual inspection of the atheroma as well as quantitative analysis of the atheroma cross-sectional area. The mean cross-sectional atheroma area at the level of coronary angioplasty sites is 8.7 ± 3.4 mm^2, which corresponds to a mean of $63 \pm 15\%$ of the available area bounded by the media.[2] This is an enormous amount of residual material that is left behind after a clinically successful angioplasty. The ability to visualize this phenomenon with ultrasound imaging in the living patient at the time of the procedure has a humbling effect on the interventionalist. It may help to explain the high rate of restenosis and raises the question whether there is a different morphology or atheroma burden in the cases without recurrent stenosis.

Even at the angiographically normal sections of the coronary artery, ultrasound imaging reveals a substantial amount of atheroma that was not appreciated by angiography. At angiographically normal segments, the mean cross-sectional atheroma area is 4.7 ± 3.2 mm^2, which corresponds to a mean of $35 \pm 23\%$ of the available area bounded by the media. This finding is consistent with the results of pathological studies in autopsy.[3–5]

The second area where intravascular imaging has a significant impact is the description of tissue characteristics of the atherosclerotic plaque. Ultrasound energy travels through the arterial wall and is differentially reflected by various components within the plaque. The backscatter of sound waves from collagen and elastin is much stronger than that from smooth muscle cells.[6] This is of fundamental importance because it permits the identification of the muscular media as a hypoechoic circle in distinction to the echoreflective adventitia and intima.[7,8] Moreover, ultrasound is exquisitely sensitive to the presence of calcium, with intense echo reflection and lack of penetration beyond the area of calcification. This information can be used to approximate the rigidity of the plaque and correlates with the incidence of plaque fractures after balloon angioplasty. The variations in ultrasound backscatter permit the in vivo discrimination between fibrous tissue, calcification, lipid, and thrombus.[9,10]

The third potential for intravascular ultrasound is the unique ability to provide information about the

The opinions expressed in this editorial comment are not necessarily those of the editors or of the American Heart Association.

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pathophysiology of the arterial wall in vivo.[11,12] Initial intravascular ultrasound studies reveal six basic patterns of plaque morphology after percutaneous transluminal coronary angioplasty (PTCA).[13,14] Intravascular ultrasound demonstrates plaque fractures and dissections more clearly than angiography. The structure as well as the rigidity of the plaque (approximated by the extent of calcification) appears to influence the response of the individual stenosis to balloon dilation. Intravascular ultrasound imaging also demonstrates pulsatile reflections within these dissection planes, which documents that blood is flowing in them. Ongoing longitudinal studies suggest that the ultrasound morphological patterns predict which lesion is more likely to develop restenosis.

The study by Rosenfield et al[1] documents the use of a computer program that digitizes sequential cross-sectional tomographic ultrasound images of a peripheral or coronary artery and displays the images in a stacked format along the length of the artery. The resultant *X-Y-Z* planes of digital information provide volume elements or voxels that can be manipulated to reconstruct any orientation of the images in three-dimensional space. The presentation format is visually appealing because it recreates our anatomical orientation as if we had the artery in hand. The three-dimensional representation of the artery lumen and atheroma morphology demonstrated by Rosenfield et al provides all the information of the cross-sectional acquisition images; in addition, the longitudinal projections are more pleasing and acceptable to clinicians who are comfortable with similar projections from angiography.

Rosenfield et al demonstrate three other beneficial aspects of the three-dimensional presentation of intravascular ultrasound images. First, the sagittal (or longitudinal) format permits limitless orthogonal views as the artery segment is bisected in incremental rotation around the long axis. This cannot be achieved by angiography because of artery overlap and limits on x-ray tube positions. Second, the pathway of a catheter in a plaque can be clearly delineated during recanalization or the complex morphology of a dissection can be reconstructed. Third, the cylindrical format permits the endoluminal surface to be observed en face, which may be useful for procedures such as stent implantation or laser radiation. Although we may be more comfortable with the three-dimensional format, a word of caution is advisable. The three-dimensional reconstruction is not more accurate than the quality of the tomographic images that produce it. Artifacts can be introduced during the reconstruction, which depends on a constant pullback in the *Z*-axis and unchanged orientation of the catheter in the lumen relative to the *X-Y* plane. The reconstruction also straightens out the artery, which misrepresents bends and tortuous topology.

From the combined research in this area, one conclusion is clear: For the first time, there is a tool for directly visualizing coronary atherosclerosis in living patients. Intravascular ultrasound has advantages over angiography because it provides more information about the disease process. Whereas the images from angiography are used to infer conclusions about atherosclerotic disease, the conclusions from intravascular ultrasound are drawn from direct observations of the atherosclerotic tissue. As demonstrated in previous reports, the cross-sectional ultrasound images correspond closely with histological preparations.[15–17] In several respects, intravascular ultrasound images are superior to histological analysis: First, the images are acquired under physiological conditions in living patients and provide information about arterial wall motion that is unobtainable from histology. Second, images can be performed before as well as after an intervention as distinguished from histology, which captures the morphology at one point in time. Third, three-dimensional reconstruction of the tomographic ultrasound images reproduces the arterial anatomy along the length of the vessel, which is not feasible with histological imaging.

There are now three forms of imaging atherosclerosis: angiography, histology, and intravascular ultrasound. Each one provides certain insights and advantages that are unavailable from the other modalities. Angiography is easiest to perform and will continue to be used routinely for diagnosis and intervention. Histology will remain the method of confirmation but will be used when all else has failed. Intravascular ultrasound, in combination with three-dimensional reconstruction, provides the most information because it visualizes the entire plaque and may well evolve into a routine procedure for many diagnostic catheterizations.

The cardiac catheterization laboratories of the future will have to support this new technology. I submit that future cardiac catheterization laboratories will have intravascular ultrasound imaging computers built into their systems. The ultrasound images will be displayed on the central video screen, and digital roadmapping will consist of an angiogram and the three-dimensional reconstruction ultrasound images displayed above the catheterization table for guidance during PTCA, atherectomy, stent implantation, or laser interventions. Newer interventional devices are currently under investigation that combine balloon, atherectomy, or laser technology with direct intravascular ultrasound guidance of plaque position and morphology. In addition, the intravascular ultrasound imaging catheter could be combined with a Doppler analysis of velocity to measure absolute coronary blood flow for the first time in humans.

These unique capabilities of intravascular ultrasound for visualizing the plaque components and for measuring the atheroma cross-sectional area with a higher sensitivity than angiography lead us to propose that intravascular ultrasound imaging will become the new gold standard for quantitative studies that attempt to measure arterial atheroma or assess the acute or chronic effects of interventional procedures. This new technology represents an opportunity to extend our knowledge about the atherosclerosis

rotic process in living patients. The article by Rosenfield et al provides eloquent insight as to how this powerful imaging tool will be applied.

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