International Journal of Cardiac Imaging 4: 63–67, 1989

Intravascular real-time, two-dimensional echocardiography*

J.R.T.C. Roelandt, P.W. Serruys, N. Bom, W.G. Gussenhoven, C.T. Lancee & H. ten Hoff
Thoraxcenter, Division of Cardiology, University Hospital Rotterdam-Dijkzigt and Erasmus University, Rotterdam, The Netherlands

Contrast arteriography is currently the principal method for assessment of the presence and severity of both peripheral and coronary vascular anatomy. With the rapid progress in interventional radiology and cardiology, there is an increasing need for more specific information on vascular pathology and better understanding of its pathophysiology. Noninvasive ultrasound imaging may allow cross-sectional visualization of certain but limited portions of the peripheral arterial system [1, 2] but has serious limitations for imaging the coronary arteries [3, 4]. The intraoperative epicoronary application of high-frequency transducers has confirmed the abnormal findings of earlier pathologic studies and further corroborated the insensitivity of coronary arteriography in appraising the extent and distribution of atherosclerotic wall disease [5]. Fiberoptic angioscopy allows visualization of the inner surface of the arterial wall and has significantly added to our understanding of acute ischemic syndromes. The method, however, has practical limitations and no information on the vessel wall under the endothelium is obtained [6].

Clearly, there is a need for an imaging method allowing the study of the vessel wall and both the characterization and quantification of its pathology. Ultrasonic real-time intravascular echography allows cross-sectional i.e. circumferential imaging providing information on the arterial wall under the endothelial surface [7]. This technique has unique and fundamental advantages over presently available techniques. In this contribution we will describe the principles of intravascular real-time, two-dimensional echocardiography and give a perspective of the potential applications of this exciting new method.

* Supported in part by a grant from the Interuniversity Cardiology Institute of the Netherlands and the STW (Foundation for Technical Science).

Early developments

The principle of a transducer mounted at the tip of a catheter from which the beam scans structures which are aligned perpendicularly to it offers the simplest approach to cross-sectional echocardiography. If the transducer rotates in synchronism with a display time-base, radial scanning produces images perpendicular to the catheter is achieved. This rotational technique was already used by Wild and Reid [7] for intrarectal scanning of the prostate. In 1968, Carleton and Clark [8] described a catheter-mounted omnidirectional single transducer in which dimensions of a vessel or ventricular cavity had to be reconstructed from echo arrival times. In 1970, Eggleton et al. [9] described a catheter system with four elements spaced 90 degrees apart. All these methods proved to be of limited use: the stiffness of the catheter and the size of the transducer assembly, the poor image quality, the long transmission pulse blurring near field structures and the slow image acquisition time all impaired their practical application.

The first real-time intravascular scanning system was introduced by Bom et al. [10]. Using state-of-the art technology a 32-element circular array with a diameter of 3.2 mm was mounted at the tip of a 3 mm (9F) catheter. Although the frame rate was high (32 frames per second) a serious limitation originating from the grating lobes in the directivity pattern was encountered. Indeed, the optimal design was a transducer operating at 5.6 MHz with a narrow main beam at the cost of pronounced grating lobes at plus and minus 56 degrees when groups of 8 elements are used in sequence. The resulting image, when a circular structure is interrogated, is ambiguous as it consists of three components: an image generated within the main beam and two superimposed images of lesser intensity within the grating lobes and rotated over plus and minus 56 degrees.

Another development was by Martin and Watkins [11] who used a transducer consisting of six radial crystals at a catheter tip to generate a crude estimate of cross-sectional area of the pulmonary artery as part of a cardiac output monitor.

The main limitations inherent in phased-array technology is that it is both complicated and expensive. Miniaturizing is difficult and poses serious technological problems both for the construction of the circular array of extremely small elements and the wiring through the limited lumen of the catheter. Lack of resolution in the near field and the size of the transducer put further limitations on circular phased-array systems for imaging of smaller diameter vessels at present.

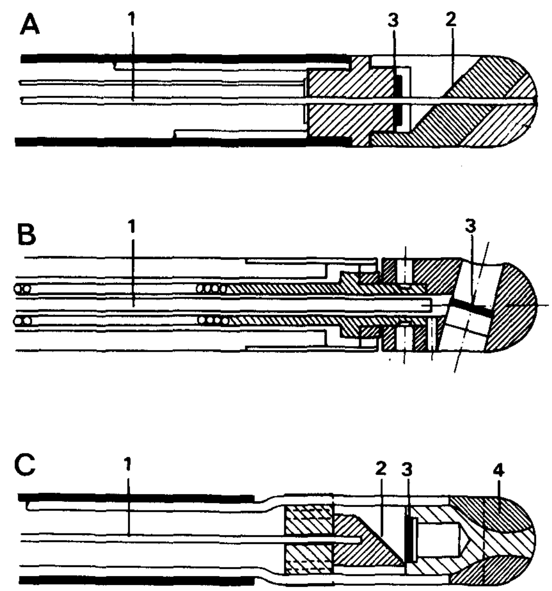

Fig. 1. A. Diagram A shows the prototype imaging catheter of which the tip containing a reflector (2) is rotated via a driving rod (1) at 3000 rpm in front of a fixed single element transducer (3). The ultrasound beam is deflected perpendicular to the long axis of the catheter and circumferentially scans the vessel wall. B. Diagram B shows a prototype with the single element transducer (3) contained within the rotating catheter tip and is rotated via a driving rod (1). The ultrasound beam is directed at slight angle forward and a cone-shaped cross-section is obtained. C. Early prototype with the driving rod (1) rotating a reflector (2) in front of a transducer (3) positioned in the fixed catheter tip. For ablation procedures electrodes for spark erosion (4) can be mounted at the very tip of the catheter.

Recent developments

Circumferential scanning with a single transducer remains the simplest approach to cross-sectional imaging [7]. Based on this principle several investigators have recently designed and constructed an ultrasonic catheter for real-time intravascular imaging [12–20]. When the transducer is mounted in the axis of a catheter, the ultrasound beam can be swept around in a plane perpendicular to the catheter either by rotating the transducer or a reflector in front of it (in a manner similar to the display of light from a lighthouse) to obtain a 360 degree display of the arterial cross-section. Both the catheter and transducer assembly are of a sufficiently small size to allow vascular and particularly coronary artery catheterization.

We have constructed catheter tip based single element transducer systems, which operate at 40 MHz [16, 21]. Either the transducer or an acoustic reflector rotates at 3000 rpm sweeping the sound beam in a 360 arc. Both the transducer assembly and the catheter measure 1.67 mm (5F) (Fig. 1A and B). The principle of a rotating single element transducer (or reflector) is simple and its construction can be combined with a desobstruction device [22] (Fig. 1C). Optimization of the driving mechanism while keeping the transducer fully flexible and steerable remains a challenging technical problem, however.

Validation studies

A series of studies performed in vitro on autopsy specimens of human arteries have accurately demonstrated both arterial lumen geometry and wall tissue characteristics allowing the differentiation between muscular and elastic type of arteries. Location and extent of atherosclerotic lesions are clearly visualized and good correlation with the histopathologic findings was found [23] (Fig. 2). Subsequent intravascular studies of carotid arteries in experimental animals have further demonstrated excellent clinico-pathologic correlation of both wall structure and dynamics.

Discussion

The need for better assessment and visualization of arterial obstructive lesions is a consequence of the rapid development of intervention radiology and

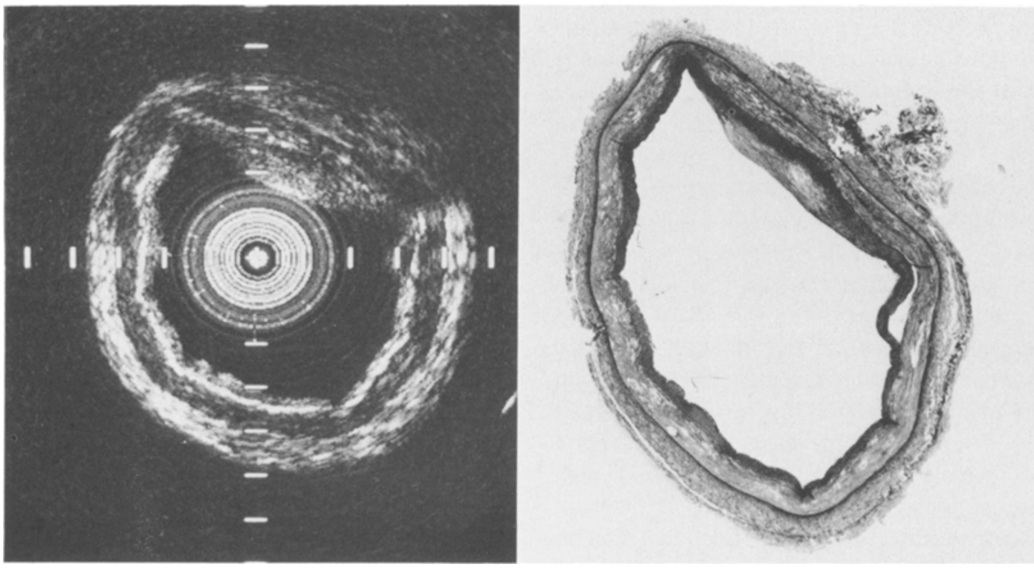

Fig. 2. An intravascular two-dimensional echocardiographic cross-section (left) and the corresponding pathologic specimen (right) obtained of a human iliac artery with atherosclerosis. The media which is composed of smooth muscle cells appears hypoechoic. An atherosclerotic plaque with fibrous cap is seen between 11 and 2 o'clock.

cardiology. Particularly the newer methods such as laser angioplasty, mechanical atherectomy and abrasion techniques of stenosed arteries require more detailed and accurate information on arterial wall morphology and pathology. At present clinical decisions for catheter-based interventions are based on contrast angiographic techniques providing percent stenosis, an inaccurate technique with large intra- and interobserver variability [24]. The angiographic appearance of the post-angioplasty region is often suboptimal for interpretation and does not allow to predict the acute and chronic complications.

Optical techniques such as fiberoptic angioscopy [6] can visualize lumen morphology and the endothelial surface but provide no information on the disease of the wall under the endothelial surface. Optical techniques are further hindered by the opacity of the blood requiring its complete replacement by a translucent liquid. The artery examined must be intermittently occluded and flushed free of blood. This poses practical limitations for guiding intra-arterial intervention especially in the coronary arteries.

An imaging method which shows lumen morphology, extent of atheroma and other pathology within the vessel wall has unique advantages for the diagnosis and treatment of arterial disease. Ultrasonic imaging offers this possibility since it allows the operator to 'see' under the endothelial surface and to visualize the arterial wall components as well as its pathology. In vitro studies have demonstrated the possibility of differentiating between various types of atheroma (calcified vs non-calcified), thrombus and the native vessel wall. Recent in vitro studies with a prototype intraluminal ultrasonic catheter support the potential of tissue characterization providing further details on arterial wall pathology [25]. The combination of intravascular ultrasonic imaging and sensing would be of major help before, during and after mechanical atherectomy and laser angioplasty as a guidance tool. Vascular surgical procedures such as endarterectomy and thrombectomy could equally benefit from direct intravascular imaging of the region of interest.

An important clinical question is whether the degree and extent of arterial stenosis (before and after recanalisation procedures) reflect their functional significance. There is ample evidence in literature that this is not the case [26–28]. Doppler catheter systems allow measurement of arterial flow velocity [29]. Prior to and after interventions at rest and following pharmacologically induced maximal vasodilatation the functional significance of the original and remaining stenosis can be assessed [30, 31]. The potential combination of measurement of arterial cross-sectional area by the imaging technique and blood flow velocity by the Doppler technique would improve our understanding of coronary artery disease and further help to assess the results of intervention.

The diagnosis and characterisation of arterial atherosclerotic disease offers additional interesting experimental and clinical perspectives. Recent pathologic studies have further elucidated the atherosclerotic disease process.

In the earlier stages of the disease, coronary arteries enlarge as a result a remodeling process in relation to plaque area and functionally important lumen stenosis may not develop until the lesion occupies 40 percent of the internal elastic lamina area [32]. Thus, serious wall disease may be present despite a nearly normal lumen cross-sectional area on coronary arteriograms. The prestenotic phase of atherosclerotic arterial disease in which vascular dysfunction is minimal was already demonstrated by Armstrong et al. [33] in primates and confirmed by McPherson et al. [5] with high frequency epicoronary echocardiography during coronary artery bypass surgery in humans. Clearly, identification and characterisation of artrial wall involvement is of major research interest to study the natural history of the disease, in grading its severity and in studying any regression of atherosclerosis when using diet and cholesterol lowering drugs.

Other potential applications when using lower ultrasound frequencies for the ultrasonic catheter tip imaging device may be the real-time imaging of valve function and measuring valve orifice area in patients with valvular heart disease. Nonvascular small lumens can also be explored such as the urinary tracts, intrauterine cavity and biliary tracts.

Conclusion

Intravascular, real-time, high resolution echography is an exciting new development. It produces circumferential images of the artery of interest and allows measurement of lumen dimensions, wall thickness and extent of atherosclerotic disease. This unique diagnostic potential can be used to characterise and quantify the degree of atherosclerotic disease, to grade the effect of pharmacologic intervention and to guide angioplasty procedures and evaluate their effects.

References

1. Blankenhorn DH, Chin HP, Conover DJ et al. Ultrasound observation on pulsation in human carotid artery lesions. Ultrasound in Med & Biol 1988; 14, 7: 583–7.
2. Pignoli P, Tremoli HE, Poli A et al. Intimal plus medial thickness of the arterial wall: A direct measurement with ultrasound imaging. Circulation 1986; 74: 1399–406.
3. Taams MA, Gussenhoven EJ, Cornel JH et al. Detection of left coronary artery stenosis by trans-oesophageal echocardiography. Eur Heart J 1988; 9: 1162–6.
4. Taams MA, Gussenhoven EJ, Schippers LA et al. The value of transesophageal echocardiography for diagnosis of thoracic aorta pathology. Eur Heart J 1988; 9: 1308–16.
5. McPherson DD, Hiratzka LF, Lamberth WC et al. Delineation of the extent of coronary atherosclerosis by high-frequency epicardial. N Engl J Med 1987; 316: 304–9.
6. Forrester JS, Litvack F, Grundvest W et al. Cardiac angioscopy in acute ischemic syndromes. Am J Card Imaging 1988; 2: 178–84.
7. Wild JJ, Reid JM. Progress in techniques of soft tissue examination by 15 MC pulsed ultrasound. In: Kelly E, ed. Ultrasound in medicine and biology. Washington, American Institute of Biological Sciences, 1950, p. 30.
8. Carleton RA, Clark JG. Measurement of left ventricular diameter in the dog by cardiac catheterization. Validation and physiologic meaningfulness of an ultrasonic technique. Circ Res 1968; 22: 545–8.
9. Eggleton RC, Townsend C, Herrick J et al. Ultrasonic visualization of left ventricular dynamics. Ultrasonics 1970; 8: 143–53.
10. Bom N, Lancee CT, Van Egmond FC. An ultrasonic intracardiac scanner. Ultrasonics 1972; 10: 72–6.
11. Martin RW, Watkins DW. An ultrasonic catheter for intravascular measurement of blood flow: technical details. IEEE Trans Sonics and Ultrasound 1980; SU-27: 277–86.
12. Hartley CJ, Sartorie MP, Henry PD. Intravascular imaging with ultrasound. In: Microsensors and catheter-based imaging technology, Alan I West, ed. Proc SPIE 1988; 904: 103–6.
13. Sacharoff AC, Caro RG, Muller DF, Boleza EJ. Demonstration of intraluminal ultrasound imaging. In: West AI, ed. Microsensors and catheter-based imaging technology, Proc SPIE 1988; 904: 118–20.
14. Ellis RA, Crowley RJ, Eyllon MM: Ultrasonic imaging catheter. In: West AI, ed. Microsensors and catheter-based imaging technology. Proc SPIE 1988; 904: 127–30.
15. Yock PG, Linker DT, Thapliyal HV et al. Real-time, two-dimensional catheter ultrasound: a new technique for high-resolution intravascular imaging (abstr). JACC 1988; 11: 130A.
16. Bom N, Lancee CT, Slager CJ, De Jong N. Ein Weg

zur intraluminaren Echoarteriographie. Ultraschall 1987; 8: 233–6.
17. Martinelli MA, Aretz TH, Butterly J. Ultrasonic imaging of coronary arterial thickness and ultrasonic signature typing of internal abnormalities. In: West AI, ed. Microsensors and catheter-based imaging technology. Proc SPIE 1988; 904: 110–5.
18. Pandian NG, Kreis A, Brockway B et al. Ultrasound angioscopy: real-time, two-dimensional, intraluminal ultrasound imaging of blood vessels. Am J Cardiol 1988; 62: 493–4.
19. Mallery JA, Griffith J, Gessert J et al. Intravascular ultrasound imaging catheter assessment of normal and atherosclerotic arterial wall thickness (abstr). JACC 1988; 2: 22A.
20. Yock PG, Johnson EL, Linker DT. Intravascular ultrasound: development and clinical potential. Am J Card Imaging 1988; 2: 185–93.
21. Roelandt JR, Bom N, Serruys PW, Gussenhoven EJ et al. Intravascular high-resolution real-time cross-sectional echocardiography. Echocardiography 1989; 6: 1–8.
22. Bom N, Slager CJ, Van Egmond FC et al. Intra-arterial ultrasonic imaging for recanalization by spark erosion. Ultrasound Med Biol 1988; 14: 257–61.
23. Gussenhoven WJ, Essed CE, Lancee CT et al. Arterial wall characteristics determined by intravascular ultrasound imaging: an in vitro study. JACC (in press).
24. Fisher LD, Judkins MP, Lesperance J et al. Reproducibility of coronary arteriographic reading in the coronary artery surgery study (CASS). Cathet Cardiovasc Diagn 1982; 8: 565–75.
25. Linker DT, Yock PG, Thapliyal HV et al. In vitro analysis of back scattered amplitude from normal and diseased arteries using a new intraluminal ultrasonic catheter (abstr). JACC 1988; 11: 4A.
26. Marcus M, Wright C, Doty D et al. Measurements of coronary velocity and reactive hyperemia in the coronary circulation of humans. Circ Res 1981; 49: 877–91.
27. Harrison DG, White CW, Hiratzka LF et al. Can the significance of coronary stenosis be predicted by quantitative coronary angiography? (abstr). Circulation 1981; 64: 160.
28. White CW, Wright CW, Doty DB et al. Does visual interpretation of the coronary arteriogram predict the physiologic importance of a coronary stenosis? N Engl J Med 1984; 310: 819–24.
29. Cole JS, Hartley CJ. The pulsed Doppler coronary artery catheter: preliminary report of a new technique for measuring rapid changes in coronary artery flow velocity in man. Circulation 1977; 56: 18–25.
30. Serruys PW, Zijlstra F, Reiber HHC et al. Assessment of coronary flow reserve during angioplasty using a Doppler tip balloon catheter. Comparison with digital substraction cineangiography. JL Interven Cardiol 1988; 1: 19–33.
31. Serruys PW, Julliere Y, Zijlstra F et al. Coronary blood flow velocity during percutaneous transluminal coronary angioplasty as a guide for assessment of the functional result. Am J Cardiol 1988; 61: 253–59.
32. Glagov S, Weisenberg E, Zarins CK et al. Compensatory enlargement of human atherosclerotic arteries. N Engl J Med 1987; 316: 1371–5.
33. Armstrong ML, Heistad DD, Marcus ML et al. Structural and hemodynamic responses of peripheral arteries of macaque monkeys to atherogenic diet. Atherosclerosis 1985; 5: 336–46.