# SURVEY OF DEVELOPMENTS IN CARDIAC AND CARDIOVASCULAR ULTRASOUND IMAGING

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**ABSTRACT**
A survey of diagnostic ultrasound techniques as used in cardiology is presented. 2D is used in many places. 3D is gaining importance.Present 3D developments include electronic and fast rotating phased array methods for 3D imaging of the heart. Surgical views will be illustrated.
Another hot item is ultrasound echo contrast, with emphasis on non-linear effects. A novel broadband transducer, combining two ceramics, will be presented.
The latest Transesophogeal (TEE) ultrasound development includes high frequency pediatric multiplane probes for application in baby's. The 48 element probe can be used in infants of 2.9 kg. to 19 kg.
In IntraVascular UltraSound (IVUS) plaque geometry and stent deployment can be studied. Also mechanical properties of the arterial wall through elastography may be obtained.

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## INTRODUCTION

In 1953, Edler and Hertz [1] introduced the M-mode technique in Lund, Sweden allowing the recording of the motion pattern of cardiac structures along a single sound beam. They described many of the presently known echo patterns. Furthermore efforts were carried out to show two-dimensional sequential images of the heart. This was based on a mirror system with a yield of 7 frames per second (Äsberg et al. [2]). The phased array electronic sector scanner was first described by Somer in 1968 [3]. This system, originally introduced for neurology, has become the "working horse" of clinical cardiology today. The phased array transducer with its small "footprint" proved excellent for probe manoeuvrability between the ribs. First practical two-dimensional images of the moving heart, however, were obtained with an electronic scanner presented in 1971 in Rotterdam by Bom [4] and Kloster [5] and was based on the linear array technique. A survey on use of echo techniques in cardiology in 1980 in the Netherlands resulted in: a) application of M-mode with linear array by 32 % of the clinicians, b) exclusive M-mode by 32 %, c) M-mode with mechanical sector scan by 29 % and d) M-mode plus electronic sector scan by 7 % of the users. Thereafter the phased array technique became dominant in cardiology and linear arrays with the larger transducer footprint were increasingly used outside cardiology in for instance obstetrics, radiology and internal medicine.
Wells described an early invasive, catheter-based system for echo studies of the arteries and veins in 1966 [6]. This was based on mechanical rotation of the acoustic element. An electronic technique with 32 elements was described by Bom et al. in 1972 [7].

Only with the introduction of interventional cardiology and the balloon dilation methods in the mid-eighties, intravascular echography became important. A practical, mechanically rotated system was described around 1985 by Yock et al. and patented in 1989 [8].

The evolution of non-invasive echocardiography seems logical: from information along a single sound beam towards cross-sectional imaging. Thereafter, increase of the number of cross-sections (in the early years only two perpendicular cardiac planes were studied) to today's first applications of 3-dimensional echocardiography. Also intravascular and intracardiac echography started with a single beam in one direction only [9] and thereafter the imaging became 2D and recently 3D [10]. Overall there was improvement of image quality by better transducer characteristics and processing techniques.

## PROBE SIZE, SCAN DEPTH AND RESOLUTION VERSUS FREQUENCY

In Figure 1, the frequency range of various cardiovascular applications is illustrated. Since attenuation increases with frequency it becomes clear that for non-invasive echocardiography in adults (large depth range) low frequencies around 4 MHz must be used. The mid frequency range around 10 MHz is indicated for esophageal echo work in children or intracardiac imaging. At the high frequency, intravascular echography can be used since the distance from echo element to vascular wall to be investigated is very limited here. As can be observed from the figure, the used transducer size decreases with frequency. This is related with the acoustic active transducer surface, which for proper beam forming must encompass a given number of wavelengths.

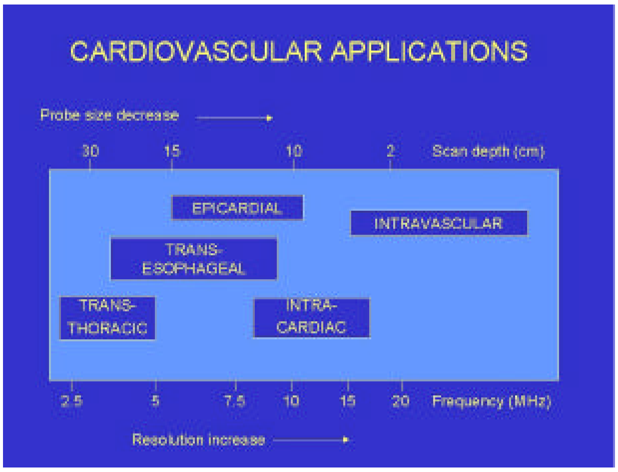


Fig. 1 - Range of cardiovascular applications with optimal frequency.

## STANDARD INSTRUMENTS VERSUS SMALL, BATTERY-POWERED INSTRUMENTS

In the cardiology department the standard- or laboratory instrument is rather bulky. It contains all the possible features and is mostly permanently located in the echo- or function department, the operating theatre or the interventional laboratory. The following list indicates what type of parameters can be obtained or studies can be carried out with such machines:

- Measurement of cardiac anatomy, global function and regional wall motion.
- Valve pathology, severity and haemodynamic consequences (Doppler)
- Presence of pericardial fluid and mass lesions
- Doppler blood flow and tissue information (Tissue Doppler, backscatter analysis)
- Detection of ischemia or viability by stress echocardiography.

Contrast agents can be injected to enhance the echo image. This technique is used to better visualise endocardial borders, enhance Doppler signals and to study myocardial perfusion. Exercise and pharmacological stress is used to induce ischaemic and regional motion abnormalities under stress conditions. Some applications require a transesophageal approach. On average an echocardiographic study in the echo lab would take approximately 25 minutes.

Handheld portable echo devices have been recently introduced on a large scale. An early system was the Minivisor. Roelandt [11,12] described first clinical experience in 1978 and 1980. However, for widespread use it was too early at the time. Now these systems are introduced for use in the ambulance, outpatient clinic, intensive care, post operative ward and at all other locations where in the hospital the cardiologists' advice is requested. Although the introduction is only beginning, it is foreseen that these devices will in particular be used for screening purposes and quick observations such as:

- Measurement of chamber/structure size.
- Detection of abnormal wall motion
- Diagnoses of valve pathology
- Observation of presence of pericardial fluid, mass lesions.

**ULTRASOUND CONTRAST IMAGING**

Echo contrast fluid contains encapsulated gas-filled microspheres, which enhance the echo image. It appears that echo contrast in particular enhances non-linear effects.

Echo transducers must have a broad frequency spectrum around the resonant frequency for proper depth resolution. With the introduction of contrast imaging in cardiology and based on the fact that in recent years the non linear properties of contrast as well as from tissue have been discovered, second harmonic imaging is becoming to be integrated in the echo instruments. This in turn requires very broadband transducers. A method described by de Jong et al [13] is based on integration of two phased array transducers with different resonant frequency into one. Apart from separation between contrast and tissue, harmonic imaging also decreases transducer near field reverberation and side lobe effects as illustrated in Figure 2.

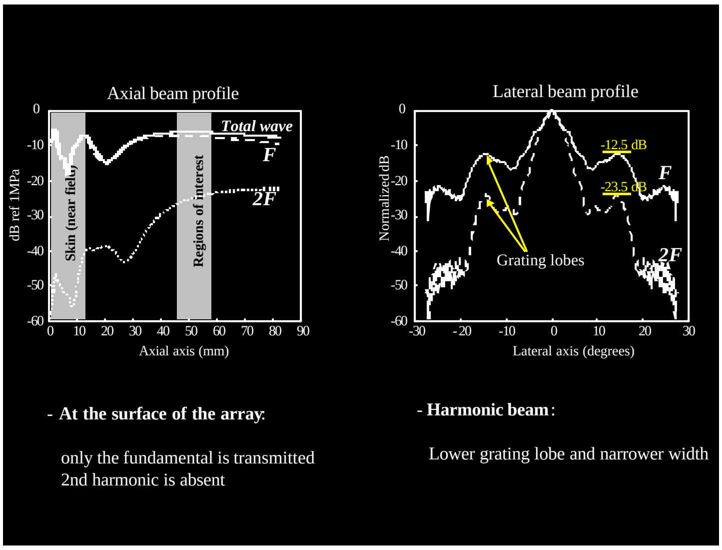


Fig. 2 - Harmonic imaging decreases transducer near field reverberation as illustrated to the left. The harmonic beam pattern has a lower grating lobe and narrower main lobe thus reducing image artefacts (figure to the right). (Courtesy A. Bouakaz)

With the advent of ultrasound agents, new *ad hoc* imaging modalities have been and continue to be developed. These techniques are designed to improve the sensitivity of ultrasound imaging systems for bubble detection by exploiting specific "acoustic signatures" of the contrast agents (e.g. Harmonic B-Mode and Harmonic Power Doppler).

Of special relevance is the particular signature that occurs at high acoustical power settings. The scattering increases dramatically due to the non-linear behaviour shown by encapsulated-gas types of contrast agents, e.g. Quantison™ (Andaris Ltd., Nottingham, UK) and Sonovist® (Schering AG, Berlin, Germany). It has been shown that free gas bubbles are released when the encapsulating shells are ruptured by a high power ultrasound field [14]. The result is an enhancement of the scattering (ES) and the duration of the effect is related to the survival time of the free gas bubbles in the medium. This particular signature has been addressed by several names: Acoustically Stimulated Acoustic Emission (ASAE), Power Enhanced Scattering (PES), Flash Imaging, Acoustic Scintillation, etc.

In conventional B-Mode imaging, ES may be visualised as bright echogenic areas. However, in hyperechoic regions or very small vessels, echoes from surrounding tissue can mask this increase in echogenicity.

## FROM TWO-DIMENSIONAL (2D) TO THREE-DIMENSIONAL (3D) ECHOCARDIOGRAPHY

Echocardiography is an interactive technique. The cardiologist or echo technician must aim the transducer at the diagnostic area of interest. For a proper echographic survey extensive experience in aiming at cardiac structures is needed. Since the heart is a complex three-dimensional organ there may be variability in the interpretation of difficult pathology amongst investigators. If the echo data were not limited to a number of selected cross-sectional imaging planes, but the full 3D data were available, then more accurate and reproducible data could become available obviating geometric assumptions. In 3D, the acquisition could become more standardised. In addition, observation may be carried out in reconstructed diagnostic cross-sections not available in standard 2D. Gradually all these advantages are becoming clear. So far the vast amount of data, complex transducer technology and display post processing time involved (all 3D results are not instantly available) have limited the advancement of 3D.

### Free Hand Scanning

In order to obtain spatially correct data, one of the approaches is to track the motion of an ultrasound 2D probe in space. This so-called "free-hand scanning" can be carried out with an acoustic (spark gap) locator as described by Moritz and Sherve in 1976 [15]. Electromagnetic location as described by Raab et al [16] and mechanical articulated arm reported by Dekker et al [17] are other methods.

Fig. 3 - Fast rotating ultrasound probes for 3D acquisition.

From top to bottom:

Prototype I (July 1998);
Prototype II (October 2000);
Prototype III (April 2002)

### Sequential Triggered Scanning.

With a stepper motor the acquisition plane is sequentially rotated by, for instance, steps of 2 degrees. When acquisition is time gated by triggering derived from the electrocardiogram and respiration, all data become available to reconstruct the moving heart in its proper geometry and time sequence. Obviously, the transducer should be held steady during the acquisition period otherwise motion artefacts are introduced.

### Fast Acquisition Systems

Presently two systems have been described where the acquisition is so fast that virtually no motion artefacts will occur. Firstly this is the electronic real time volumetric ultrasound imaging system developed at Duke University by Von Ramm and Smith [18]. They use a novel matrix phased array transducer in which the elements are arranged in a two dimensional grid. With insonification in a wide cone and parallel processing in reception fast 3D (or selected 2D) display becomes available. Lancée and Djoa described another approach [19]. They use a fast rotating phased array transducer enabling acquisition of 16 volumetric data sets of the beating heart per second. A photograph of this probe is shown in Figure 3.

An example of a 3D rendered image of the heart valves is illustrated in figure 4 [20]. With the introduction of real time acquisition of 3D and faster computers, the use of 3D will become much more practical. Today the method is particularly indicated for congenital diagnosis of heart disease and for correct calculation of volumetric parameters.

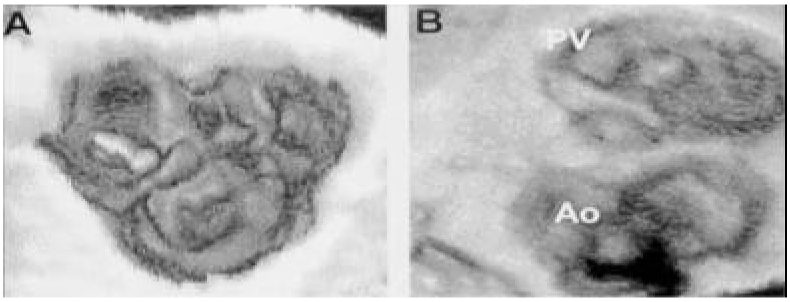


Fig. 4 - 3D rendered image of the heart valves. Attachment of small vegetation to the cusps of the aortic valve (panel A) and the pulmonary valve (panel B) are visualised. PV = pulmonary valve. Ao = aortic valve. (Courtesy N. Bruining)

**HIGH FREQUENCY (7.5 MHZ) PAEDIATRIC MULTIPLANE TRANSESOPHAGEAL ECHO (TEE) PROBE**

A TEE probe consists of a phased array echo probe mounted at the tip of a gastroscopic tube. In the latest versions of this probe the entire array can be rotated manually to select the proper diagnostic cross-sectional echo plane.

The development of TEE-probes at the Thoraxcentre started around 1982 and resulted in a commercial Oldelft BV (Delft, The Netherlands) adult single plane 5 MHz TEE probe in 1985. However, for use in children, the size of this early TEE probe was a major restriction. Moreover, complex cardiac structures and congenital anomalies are often missed using single plane TEE
.
To overcome the abovementioned limitations, many institutes all over the world worked on the development of TEE probes with reduced dimensions and more scanning planes. Nowadays multiplane TEE probes with shaft diameter in the order of 7 mm are available for routine use in pediatric patients above 3.5 kg.

**INTRAVASCULAR ULTRASOUND (IVUS)**

The technique of intravascular ultrasound is based on the flex-shaft mechanically rotated single element or the electronically steered phased array method, with or without the use of a guide wire (figure 5). They produce cross-sectional vascular real-time images of the lumen, plaque and arterial wall [21]. An example of an intravascular image of an artery is shown in Figure 6.
Mostly the intravascular procedure is applied for further decision-making when X-ray angiographic data are less conclusive. For obvious reasons there is a strong urge to combine “see and do” in interventional procedures. This leads to catheters in which, for instance, an angioplasty balloon is combined with ultrasonic imaging in or close to the balloon. Other

combinations may provide guidance during stent implantation. Since intravascular imaging provides accurate geometrical information within the cross-section, combination with other interventional procedures is likely to expand in future. In this category falls the assessment of the dose deposited in the arterial wall during intracoronary brachytherapy or by radioactive stents as described by Carlier [22]

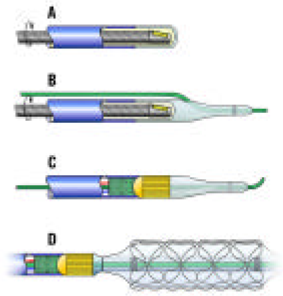


Fig. 5 - Schematic drawing of present intravascular echo catheters. Flex-shaft mechanically rotated element method (A), with guide wire (B), electronic beam switching (C) and a combination of electronic switching with a therapeutic stent placing technique (D).

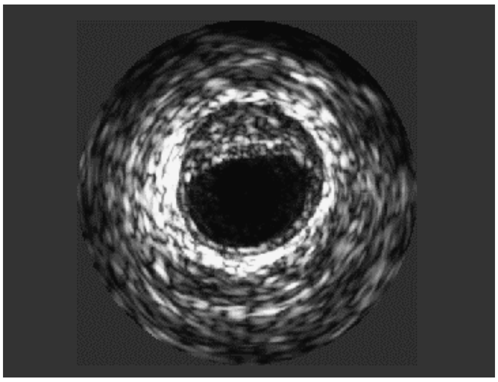

Fig. 6 - Example of an intravascular image with a lesion between 10 and 2 o'clock.

Additional Parameters

Where present, intravascular scanners yield detailed cross-sectional geometric information of the arterial wall. For the evaluation of the arterial function the remaining blood flow through the obstruction is also an important parameter. Using a decorrelation technique with the Radio Frequency (RF) echo signal, sequentially obtained at the same location, it seems possible to combine imaging with measurement of instantaneous volume flow through the lumen.

First attempts have shown that RF echo data also enable the assessment of mechanical properties of the arterial wall. In this approach, the echo data are compared in the same location, but at different pressures [23].

3D Imaging And Quantitative Data

All organs have a three-dimensional configuration and therefore the concept of ultrasonic 3D imaging has become increasingly important. In non-invasive echo imaging real-time volumetric echo data acquisition has been described. It is not expected that this will become possible in real-time intravascular methods since it will always require pullback of the catheter in order to accumulate all the necessary data. Such a device enables data acquisition for the construction of arterial 3D images, which are very informative as illustrated for control of stent deployment in Figure 7.

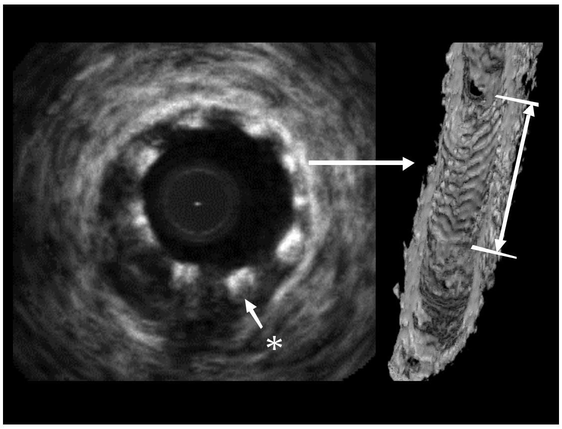


Fig. 7. Echo image of stent with struts (*) and corresponding 3D image. (Courtesy N. Bruining)

Based on 3D echo-data files, it has become possible, with interactive semi-automatic contour analyses, to obtain precise quantitative information on plaque volume and open lumen over the entire arterial segment studied.

**CONCLUSION**

Echocardiography has seen an enormous development from the first poor images up to now. It has (with integrated Doppler which is dealt with in another chapter in this issue) amongst the other imaging techniques such as CT or MRI taken the position of primary diagnostic method in cardiology. The 3D use is still in its infancy but undoubtedly it will break through in the coming years. We have noted the introduction of small rather cheap devices that will further expand diagnostic echocardiography.
The use of echo catheters for intravascular applications is much more recent, and it is limited by the expenditure due to single use of these devices. If these catheters become cheap, and combined with therapeutic devices, things will change.

Future intravascular scanners will provide improved image quality, have interventional therapeutic capabilities incorporated and possibly be combined with other diagnostic methods such as Raman spectroscopy. Furthermore, 3D display and quantitative data extraction will become more and more routine rather than research.

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