EFSUMB History of Ultrasound

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Introduction

Some 40 years ago, cardiology entered the modern age of diagnostics by introducing ultrasound technology as a routine clinical tool. Before that, cardiological diagnostics were mostly based on clinical judgement, auscultation, and chest-radiograms. Only a few, larger centers utilised invasive catheter based pressure measurements.

Pioneers

It all started back in the fifties, when dr. Inge Edler in Lund, Sweden, concerned by the methodological and timeconsuming limitations of cardiac catherisations and angiograms, sought after new diagnostic tools. In this process he met an engineering student, Carl Hellmut Herz, who at that time worked with ultrasound for detection of material properties at a shipyard in Sweden. In 1953, he got access to a so-called *ultrasound reflectoscope* used by Tekniska Røntgensentralen in Malmø, used for testing the metal properties of submarine hulls. Herz found, by applying the reflectoscope on his own chest, that movements could be recorded from the heart region. Somewhat later, he met Edler and the two borrowed a new ultrasound reflectoscope from Siemens (Erlangen, Germany), and initiated a true revolution in cardiac diagnostic imaging.

First, during the late fifties, Edler used the reflectoscope to characterize movement patterns of normal and stenotic mitral valves [Figure 1], and the methodology was subsequently adopted by advanced clinical institutions in Germany and USA.

Figure 1 The pioneers. Herz and Edler with the first "reflectoscope" used in 1955 to record movements of cardiac structures.

Doppler ultrasound emerged somewhat later based on the works of dr. Satomura of Japan in the mid-fifties, first for recording of cardiac wall movements, later for measurement of blood flow velocities. At that time, only *continuous wave Doppler* was available. *Pulsed Doppler* was developed around 1970 by Baker (USA) and Peronneau (France). It took, however, more than a decade before both continuous and pulsed Doppler were found generally feasible and established in the clinical practice.

During the seventies, the major ultrasound modality was *m-mode* (motion-mode). M-mode was used to characterize valve function, cardiac dimensions, wall motion, and pericardial fluid. The main limitation was the uni-dimensional function of m-mode, which required a tedious recording procedure as well as a very high level of experience in order to obtain reliable and reproducible recordings. A linear array *2-dimensional grey tone ultrasound scanner* was developed by Nicolaas Bom (Netherlands) in 1971, and emerged as a solution to these obstacles. Two-dimensional ultrasound sector scanning, introduced in 1974 by Griffith and Henry (mechanical scanner) and Thurstone and Ramm (phased array scanner), was the definite major technological breakthrough, since it allowed imaging of larger sectors of the heart from a small access window in a format that was understandable for the general clinical community.

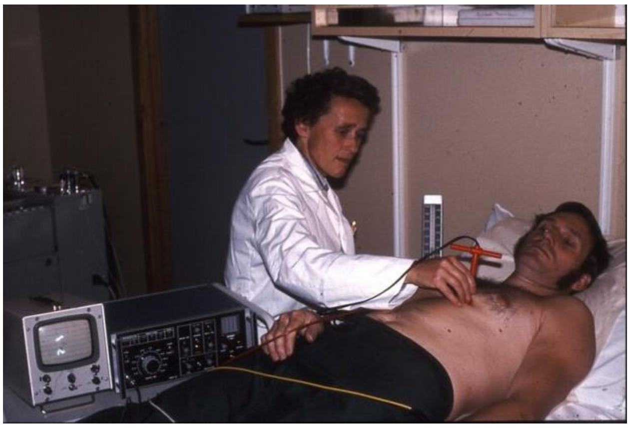
Technology

Doppler ultrasound

Doppler has together with two-dimensional sector imaging, emerged as the most important integral part of modern ultrasound examination. Important technological quantum leaps were originally presented in Norway. It started in 1972 in Trondheim at the Department of Engineering Cybernetics at the Norwegian University of Technology. Under the auspices of prof. Balchen, the engineering research fellows Bjørn A. Angelsen and Rune Aaslid were able to develop a device for measurement of blood flow velocities based on ultrasound and the Doppler effect. With this apparatus, named PEDOF, both blood flow velocity *and importantly*, flow direction in a vessel or in the heart, could be estimated. Dr. Jarle Holen who combined his airplane engineering background with clinical medical radiology, adopted the technology at Rikshospitalet in Oslo in collaboration with Aaslid, and used it in his thesis work. They utilised the Bernoulli's equation to calculate pressure gradients from Doppler estimates of blood flow velocities. First on an in-vitro stenotic mitral valve experimental set-up, and later in patients. In 1976 they demonstrated that Doppler based estimations of pressure gradients over the stenotic mitral valve were practically identical with simultaneously obtained invasive pressure gradients during heart catheterisation.

Concordantly, the PEDOF apparatus were modified to incorporate both continuous and pulsed wave Doppler, and was put into testing in the clinical setting by dr. Liv K. Hatle in Trondheim from 1976 [Figure 2].

Figure 2 Doppler. Dr. Liv Hatle performing the pioneering works on assessment of mitral stenosis by blind Doppler.



In 1978, she presented clinical data on patients with mitral stenosis confirming the pioneering works of dr. Holen. She collaborated with Bjørn Angelsen and simplified the Bernoulli equation further by eliminating complex elements, leading to:

$$\Delta P = 4v^2$$

This equation has later been nicknamed the $E = mc^2$ equation of cardiology.

It turned out that this simplified Bernoulli equation worked well for quantitating pressure gradients over stenotic valves in the mitral and aortic positions, as well as over regurgitations. Dr. Terje Skjærpe, also at Trondheim, used measurements of pressure gradients over tricuspid regurgitations to estimate systolic pressures in the right ventricle which on most occasions are equal to peak pulmonary artery pressure.

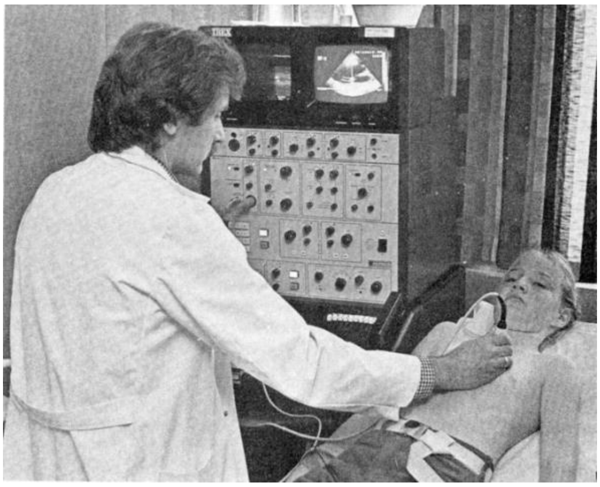
However, the Doppler measurements available at that time were unguided, i.e. blind, and technically challenging. The Doppler technique was therefore not used by many cardiologists at that time. Bjørn Angelsen then worked in USA, and produced a real-time spectral-analyzer (DAISY) [Figure 3] at the same time as Kjell Kristoffersen and coworkers in Trondheim developed a novel all-frequency Doppler apparatus.

Figure 3 DAISY. The first commercially available real-time spectral-analyzer

These apparatuses, named DAISY and ALFRED, were eventually combined in 1979, and defined the standard against which all later Doppler measuring apparatuses were to be compared.

Still, the blind Doppler was challenging to use. However, in 1982, the Irex IIIB duplex ultrasound was presented and combined 2-dimensional sector scanning *with* the DAISY/ALFRED Doppler [Figure 4].

Figure 4 Irex IIIB. This apparatus combined 2D grey scale ultrasound imaging with a steerable Doppler beam.



Thus, this apparatus combined high quality Doppler recordings in both continuous and pulsed mode with 2 -dimensional sector scanning, which was an unmatched powerful combo that allowed reliable orientation of the Doppler beam for measurements of flow velocities as well as pressure gradients in the heart and vessels. This year, dr. Hatle and Bjørn Angelsen published their first textbook on Doppler ultrasound in Cardiology. This highly appreciated book formed together with its second edition in 1985, the basis for understanding and use of the Doppler techniques in cardiology.

Colour Doppler

Although the duplex scanners were extremely useful by providing simultaneous 2-dimensional grey scale imaging and Doppler recordings, there was a keen desire to be able to visualize true blood flow patterns in the heart and vessels. Initial attempts using colour m-mode was developed and presented by Brandistini in 1979, but did not attain general use. In the eighties, Hans Torp and Bjørn Angelsen developed prototypes for colour Doppler imaging using a mean frequency estimator originally presented by Kjell Kristoffersens in his master thesis in 1977. Almost simultaneously, Aloka (1985) and Vingmed Sound (1986, CFM 700) presented commercial scanners comprising colour Doppler flow imaging. Whereas Aloka used a phased-array linear transducer, Vingmed Sound used a mechanical motorized probe. The mean frequency estimators used in both these pioneering devices were actually obtained and based on weather radar systems, which at the time already were capable of displaying color maps and utilise autocorrelation techniques.

Image quality for color Doppler has been successively improved over the years. Main obstacles have been to remove clutter noise from the blood pool, and to provide an adequately high frame rate. The introduction of a digital front-end in the ulatrasound scanners, the increase in data processing power, and the general use of phased array probes were key success factors in this process. It was now possible to process numerous ultrasound beams simultaneously, a technical pre-requisite for improved colour Doppler.

Colour Doppler blood flow imaging is undoubtedly a very important technological breakthrough in cardiovascular medicine. With this technique, the clinician can get a quick, noninvasive and reliable overview of the circulation patterns in the heart and vessels, and thereby identify obstructions, regurgitations and shunts. Colour Doppler has also been used to quantify regurgitant volumes by use of the so-called PISA method, as first proposed by dr. Recusani et al in 1991. Colour Doppler blood flow imaging was quickly implemented in all major cardiovascular ultrasound scanners, and the technique was adopted by clinicians and researchers worldwide within a few years, in fact an astonishing short time-span for distribution of a novel clinical application which demonstrates its versatility and usefulness.

Harmonic imaging

Image quality has always been the cornerstone, as well as the Achilles' heel, of echocardiography. Thus, *ultrasound contrast* gained much interest. However the initial experiments between 1980 and 1990, although promising, were hampered by instability of the contrast agents, difficulties in manufacturing and production, and for some brands also major adverse patient events. In the search for optimal image quality during ultrasound contrast, different scanner settings were tested. Of particular interest was the so-called harmonic imaging which appeared around 1995. The principle was to utilize the reflected 2nd harmonic of the original ultrasound beam frequency. Although harmonic imaging gave some improvement of contrast-based images, the clinicians to their surprise quickly discovered that harmonic imaging in fact improved standard 2-dimensional grey-scale image quality. In some cases the improvement of image quality was directly stunning. Thus, this methodology was swiftly adopted by all vendors, and quickly became the industry standard for high-quality echocardiographic imaging. Unfortunately, harmonic imaging did, due to technical issues, not improve Doppler or colourDoppler recordings. Over the last couple of decades, more stable contrast agents with improved imaging properties and but little adverse events, have been developed and found its place in advanced ultrasound laboratories worldwide.

Tissue Doppler

The concept of tissue Doppler with initial clinical applications was first presented for the cardiological community by dr. Karl Isaaz and co-workers in 1989, and by prof. George Sutherland in 1990 at the European Society of Cardiology conference in Stockholm, and The concept was simple, and in practice every conventional scanner comprising Doppler modalities could be fine-tuned so that high blood flow velocities could be filtered out, leaving the low tissue velocities for display and recordings. Tissue Doppler was subsequently used to characterize left ventricular diastolic function as first decribed by dr. Sohn et al in 1997. At the same time, a young engineering student in Trondheim, Andreas Heimdal, developed the concept further and used tissue Doppler data to extract strain rate and strain measurements from the myocardium. Together with dr. Asbjørn Støylen he presented the first clinical validation of the method in 1998. His pioneering theories and experimental works were presented in his PhD thesis work in 1999.

Strain by ultrasound

Initially strain-rate and strain measurements were based on tissue Doppler recordings. Two-dimensional grey-tone scale imaging did at that time simply not have the necessary resolution for strain measurements. This was, however, made possible with the improved ultrasound image quality and colour coded tissue Doppler that emerged around year 2000. Strain and strain-rate as measures of myocardial contractions were first experimentally validated against sonomicrometric techniques by dr. Urheim from the Oslo group. Their studies were the basis for later extensive research in this field leading to a more general clinical application of strain and strain rate in the evaluation of left ventricular function. The method was initially hampered by lack of a definite industry standard, i.e. different vendors used different algorithms that produced different results for strain measurements.

3-dimensional echocardiography

Almost at the start of clinical ultrasound imaging, there was a desire to be able to present the recordings in 3-dimensional format to better reveal the true organ structures. Intially, there was no hardware or computational processing power available to undertake such a task. In the nineties, the TomTec-company developed a software that could utilise 2-dimensional grey-scale images to produce 3-dimensional rendered images. There were, however, technical obstacles to the method which used averaging and smoothing to overcome the obvious lack of data from the 2-dimensional probe. Ingenious technical solutions were presented to obtain 3-dimensional data sets from 2-dimensional data. Of note were motorized rotational probes and spark emitting probe positioning systems, of which none found a wide clinical acceptance or use.

True 3-dimensional imaging would require approximately 5-10 000 piezoelectric elements in a matrix formation in the probe, and the scanner must be able to handle a multitude of channels (typically 100-200). This was first attempted by the Duke University group, led by dr. Kisslo. It was not until around 2000 that a commercially available system combining a matrix ultrasound probe with a scanner with such high data processing capabilities was presented (Philips). Later, image quality and probe technology has developed quickly. Thus, within the following decade all major vendors succeeded to present true real-time 3-dimensional echocardiography systems, both with trans-thoracic and trans-oesophageal probes. The latter has proven decisive state-of-art imaging for valvular heart disease, in particular in the pre- and per-operative setting, and has also proven very useful in evaluation of structural heart disease.

From a clinical standpoint, true 3-dimensional echocardiography is probably the single major breakthrough in ultrasound diagnostics since color Doppler was presented some 25 years ago.

Education, events and congresses

Student ultrasound education, ultrasound for medical students

Cardiac ultrasound has over time become the main work-horse of clinical cardiological diagnostics. Moreover, this technique has been widely utilized in clinical and experimental research since it first was introduced to the community, and the number of publications have steadily increased to the present number of apprx 2000 articles per year, but still increasing. There has been a need for education in echocardiography, which in most countries have been a combination of supervised learning-by-doing and dedicated educational courses on different levels of expertise covering all cardiological subspecialities. Lately, education of medical students in ultrasound diagnostics have been initiated at an increasing number of medical faculties, reflecting the assumed practical importance this methodology will have in the students' later clinical career. Moreover, European Society of Cardiology has established programs for individual accreditation in transthoracic echocardiography, in transoesophageal echocardiography and in congenital heart disease. There are also accreditation programs for echocardiographic laboratories. European Society of Cardiology has established a working group for cardiovascular imaging (formerly working group for echocardiography), that organizes an annual conference drawing about 3500 attendees, and issuing a monthly scientific journal, European Heart Journal, Cardiovascular imaging. Similar accreditation programs, conferences and journals are also available in the USA and Asia.

Conclusion

The fast development in ultrasound imaging technology and probe designs have been absolutely stunning. It is clearly the result of an impressive international innovative collaboration between dedicated engineers and physicians. Norwegian scientists and clinicians have undoubtedly played a decisive role in this process. Today, echocardiography has for a large part replaced cardiac catherisations in diagnostic work-ups of left ventricular failure, valvular heart disease and congenital heart disease. For the patient, this means a quick, noninvasive and reliable access to diagnosis of heart diseases which else would have required exhaustive investigations with potentially adverse events. Echocardiography is now used worldwide in every normally equipped hospital.

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