Eur. Radiol. 9 (Suppl. 3), S 307–S 311 (1999)

Technology European Radiology

Section II: Digital technology

An overview of digital technology in ultrasonic imaging

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Digital vs analogue

Analogue signals give a continuous representation of whatever quantity is being measured. For example, the voltage produced by an ultrasound transducer is an analogue signal, being a continuous version of the pressure acting on the transducer. No matter how small the change in pressure, there would be a corresponding change in the output voltage. Analogue signals are converted to digital signals by an electronic device known as an analogue to digital converter (ADC). This samples the analogue signal at closely spaced intervals, and generates numbers representing the value of each of these samples, with a precision determined by the number of digits available. Figure 1 illustrates an example of digitisation to one digit only, on a scale of 0 to 9. With just one digit the smallest change that can be digitised is only one tenth of the full range. If the samples were to be measured as a number between 0 and 1, given to three decimal places, the smallest change that could be measured would be one thousandth (0.001) of the largest signal (1.000). Clearly it is fundamentally important to use an ADC which measures to a sufficient number of decimal places (number of digits) for the accuracy required.

It is also vital that the samples be generated with sufficient frequency (sampling rate) to represent the fastest variations of the signal with time. Shannon's sampling theorem states that the sampling rate must be at least twice the highest frequency that it is desired to include in the digitisation process. There is thus an upper frequency limit to the frequencies that can be correctly digitised. This is known as the "Nyquist limit" and is equal to half the sampling frequency. Spectral components at frequencies above this will be measured incorrectly – a phenomenon known as "aliasing".

The benefits of converting a signal to digital form are:

1. It can be processed in a limitless number of ways on a digital computer, unlike an analogue signal for which the processing options are a compromise between what is wanted and the availability and performance of electronic hardware.
2. Often, similar hardware can be used to achieve a range of different processes, depending on the controlling software; similarly, a revision of a particular process can often be achieved simply by a change of software.
3. The signal can be stored and processed repeatedly, by several processes in parallel if required.
4. The result of a given digital process on a given digital signal is always identical.
5. The number representing each sample will not drift with changes in temperature or other environmental factors, or with ageing or subtle performance changes in the measurement equipment.

Table 1. Examples of decimal and binary number equivalents

Decimal	Binary
0	0
1	1
2	10
3	11
4	100
5	101
6	110
7	111
8	1000
9	1001
10	1010
15	1111
16	10000
31	11111
63	111111
127	1111111
255	11111111

Bits and bytes

Digital computers use binary numbers, which obey very similar rules to decimal numbers except that whereas each decimal digit has ten possible values (0–9), a binary

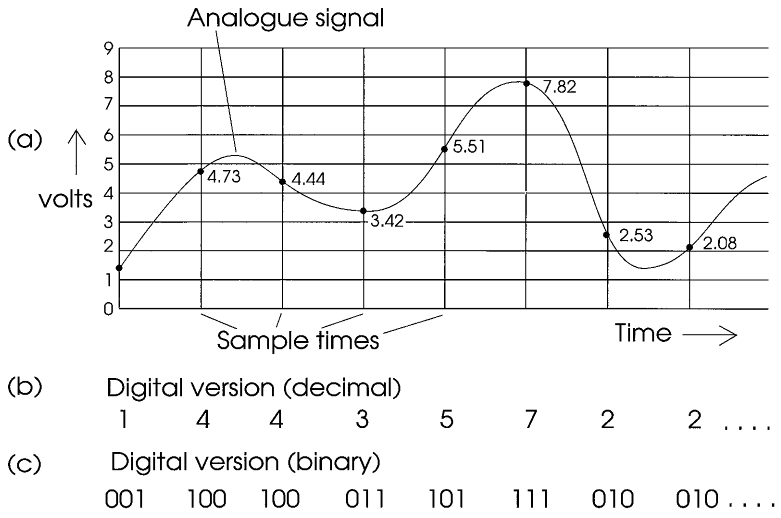

Fig. 1. **a** Digitisation involves measuring samples of an analogue signal at frequent intervals, quantitised here to the whole number below. **b** The digital version of the original signal consists of a sequence of numbers (in this case just single-digit decimals), one for each sample. **c** The same information as **b**, expressed in binary form

digit (bit) has only two (0 and 1). With both types of number, an extra digit is introduced to the left each time the count limit of the existing digits is exceeded. Thus, "10" means ten (one more than the maximum of nine) when using decimal notation, but it means two (one more than the maximum of one) when using binary notation. Examples of binary-decimal equivalents are given in Table 1. A precision of approximately 1 % can be achieved with two-digit decimal number (up to 99 decimal), but the same precision requires a 7-bit binary number (up to 1111111 binary). An 8-bit binary number, known as a byte, gives a precision of just better than half a percent. With both types of number, the greater the number of digits, the greater the accuracy of the digital representation.

The digital age

It is no coincidence that digital technology has revolutionised medical ultrasound at the same time that it has pervaded most aspects of modern human life. Digital watches, digital mobile phones, compact discs, personal computers, military hardware, etc., have all provided large and profitable markets to motivate investment in the necessary research and development. The low cost ADCs, memory and processing "chips", and the associated manufacturing technology, that have resulted from this investment have been readily imported to ultrasound imaging.

One of the most important developments has been the availability of large and complex integrated circuits that can condense one or more whole boards of electronics on to a single chip. These "application-specific integrated circuits" (ASICs) can be custom designed to include both digital and analogue circuits, or purely digital circuits, as required. They allow circuit complexity, speed and reliability to be increased, at the same time as permitting equipment size and relative cost to be reduced. The design and development costs of an ASIC are a major investment for a manufacturer, so they are used in parts of the scanner where further hardware changes are not likely. However, they can be designed so that their function can be modified by software or external switch settings.

Digital ultrasound imaging

The advantages of digital processing apply to all stages of an ultrasound scanning machine. They include cost-effectiveness and reliability, but most important is the improvement in performance that they offer. Put simply: *if a process can be expressed mathematically, it can be achieved digitally.*

Many of the design advances of recent years are based on ideas that have been around for decades. The

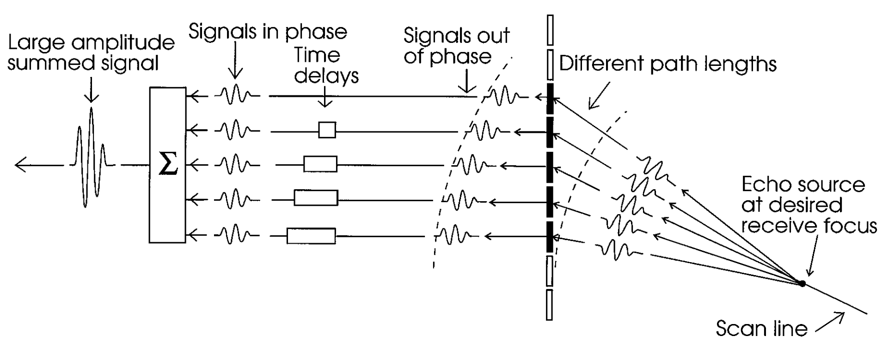

Fig. 2. Time delays are used to compensate for differences in path lengths to each element. Particularly large delays are required for large apertures or scan lines at large angles

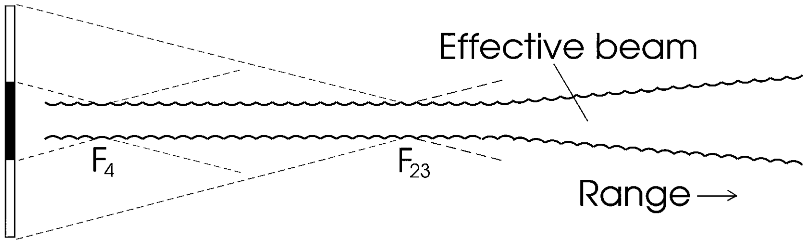

Fig. 3. A consistently narrow effective receive beam is achieved if the receive focus and aperture are changed at very frequent intervals during the reception interval. A beam with just a single focus would be wider than this effective beam at all ranges other than its own focal zone

reason they were not implemented before is that it would have been uneconomical, if not impossible, to incorporate the necessary analogue electronics. Many of these ideas have, by themselves, produced only modest advances; however, since their implementation by digital means is relatively easy, many such ideas can be incorporated. Taken together, they can have a dramatic effect on machine performance.

Digital beam forming

Beam forming is at the heart of scanner performance, and this is becoming an increasingly digital process, with ASICs replacing analogue delay lines. It is still necessary to use an analogue circuit, the RF amplifier, immediately after each transducer element to boost echo amplitudes to a level suitable for the ADC, and most machines include time gain compensation (TGC) in this stage. At the heart of the beam-forming process is the need to impose different time delays on the signals from each element, according to the position and angle of the scan line and the required reception focal distance (Fig. 2). The size, cost and fabrication difficulty of an analogue delay is proportional to the product of the required bandwidth and the required delay. This places limitations on the resolution achievable, since good axial resolution requires a large bandwidth, whereas good lateral resolution requires a large aperture, which in turn means large delays. Even longer delays are needed if the beam is to be steered at an angle. Further limitations are imposed by the slight errors in delay that occur in practical devices.

Once digitised, however, there is very little difficulty in producing very large delays, whereas the precision can easily be made as high as required by defining finer time increments. The larger delays allow larger apertures to be used, improving lateral resolution. Sensitivity and dynamic range are also improved, since the greater delay accuracy in each channel means the individual signals can be more correctly aligned in time, thereby producing a larger resultant signal and less acoustic noise. Moreover, the ease and precision with which the receive focus can be changed means that hundreds of progressively advancing foci can be generated in the course of one reception sequence. This further improves lateral resolution, since the focus in use when any echo arrives must lie very close to the target producing that echo (Fig. 3).

Parallel beam forming [1] is a major advance that has been made possible by digitising the RF echo signals. For example, if four receive beams are to be formed in parallel, four delayed versions are produced from each digital sample of the RF echo signal, each with a delay appropriate to one of the four beams. The transmission beam is wide enough to include all four receive beams (Fig. 4), so that one transmission pulse serves to interrogate all four scan lines. The time saving achieved by generating four scan lines simultaneously can be used to increase frame rate. Alternatively, it can be used to improve lateral resolution, by compensating for the frame rate penalty otherwise associated with the use of multiple transmission focusing and an increased scan line density. In the case of colour Doppler imaging, it can be used to improve sensitivity to low flow rates and Doppler frequency resolution [1], by allowing more time to be spent interrogating each Doppler line.

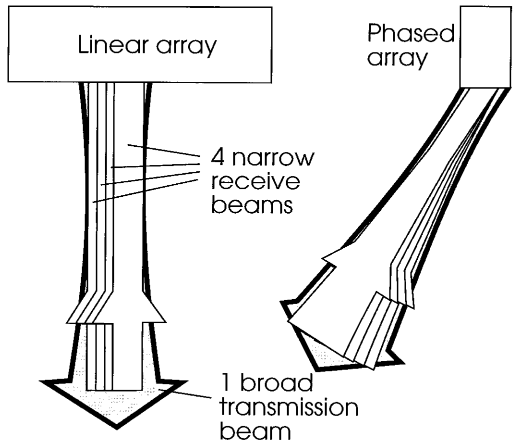

Fig. 4. Parallel beam forming allows echoes from several scan lines to be received simultaneously following each transmission pulse. One transmission beam with fixed weak focusing can accommodate up to four narrower dynamically focussed receive beams

Synthetic aperture [2] is another method of improving lateral resolution, made possible by digital beam forming. Lateral resolution improves as the number of elements in a probe increases [3] but, although it is not too expensive to build a linear-array probe with as many as 256 elements, the cost of providing 256 independent delay channels is considerable. The number of channels needed can be kept at 128 if two transmission–reception sequences are used instead of one. Half the elements are used to transmit and receive in the first sequence, and the other half are used in the second. The RF echoes from the first 128 elements are delayed, combined and stored digitally until those from the second 128 elements arrive andare similarly combined. Both sets of delayed echoes are then added.

Digital signal processing

Ultrasonic pulses change in shape as well as amplitude as they propagate through tissue. These changes can be approximately predicted and expressed mathematically. Digital processing techniques can therefore be used, either to minimise any image degradation these changes might cause, or, more positively, to analyse the changes to extract diagnostically useful information.

An example of the former is dynamic filtering, a technique that compensates for the relative reduction in the high-frequency components of the returning echoes. Echoes from deep targets suffer more high-frequency attenuation in passing through tissue than do echoes from shallow targets. This causes their centre frequency and bandwidth to be lowered. If the receiver response remains constant, the bandwidth will be unnecessarily large for the later echoes (deeper targets), and since electronic noise level increases with receiver bandwidth, this will produce unnecessary noise. Dynamic filtering progressively reduces the centre frequency and bandwidth of the receiver with time after transmission, to match that of the echoes. In the future this process is likely to be even more accurate, as the attenuation vs frequency characteristics of each layer of tissue will be measured from the returning echoes themselves, allowing the receiver frequency response to be continuously adapted to the precise tissues involved [1]. Moreover, the measured attenuation characteristics will provide new diagnostic information in themselves. A further example of using changes in pulse shape to increase diagnostic information is tissue harmonic imaging (THI*)* [4], discussed elsewhere in these proceedings.

Coded excitation [5] is another example of a technique that had to wait until digital processing was established. This allows higher than normal frequencies to be used, with resulting improvements in spatial and contrast resolution, particularly for deep targets. Thus, in an abdominal application, instead of, for example, a single 3-MHz transmission pulse, a short sequence of closely spaced 6-MHz pulses is transmitted. The length and precise centre frequency of each pulse and the times between consecutive pulses varies through the sequence in a pattern (code) that the processing system is programmed to recognise. The code is so different from the background electronic noise that the coded echo sequences can be clearly recognised even when the individual echoes are too weak to be clearly detected by themselves.

Image processing

Digital processing of the stored image data can bring further image-quality improvements. For example, by analysing the distribution of grey levels in the each part of the image, the processor can automatically adjust the grey level of each pixel to optimise the local contrast [6]. This improves the detectability of small lesions, small vessels and other small structures surrounded by soft tissue. Adaptive frame averaging is another technique that improves image quality independently in each small region of the image. Here, the processor uses more frame averaging (persistence) in parts of the image that change little from frame to frame, while using less where there is more change. Thus, the noise-reducing benefit of frame averaging can be given to slowly changing parts of the image, without imposing inappropriate persistence on rapidly changing parts.

Where a field of view is required that is wider than that offered by a particular probe, a technique known as extended field of view [7] allows images from adjacent viewing points to be joined together into one long image. The probe is moved sideways, following the curvature of the patient's surface, but being restrained by the operator to stay within as fixed a plane as possible. The images obtained at each probe position are stored and compared by the digital image processor. Particular anatomical features are recognised as being common to consecutive images, but, of course, with different positions and orientations within each image. These differences allow the processor to calculate the shift and any rotation of the probe between view points, and thus present the new image as a seamless overlapping extension of the old.

An exhaustive account of all the applications of digital image processing is impossible, since the whole message is that it unleashes boundless potential. A brief mention of some of the more important other developments must include 3D and elasticity imaging, both of which are discussed elsewhere in these proceedings, and speed of sound correction of ultrasound computed tomography images [8] and B-mode compounding [1].

Image display, archiving and tele-sonography

Since modern scanning machines incorporate similar digital processing chips and architecture to those used in computers, it is logical that they take advantage of the high resolution offered by computer displays. Previously, ultrasound scanners used display monitors with the same picture format as used in domestic television. The standards defining this format (PAL in Europe, NTSC in the USA) are designed with broadcasting in mind and, because each of the many broadcast channels has its own frequency band, the bandwidth in each channel must be limited. This, in turn, limits the resolution and frame rate of television images. The PAL image consists of 625 horizontal lines at a frame rate of 25 frames per second (fps). The NTSC image consists of 525 lines at a frame rate of 30 fps.

Displays designed for computers do not have to comply with the bandwidth restrictions of broadcasting, so they can have greater numbers of pixels horizontally and vertically, as well as higher frame rates. This gives greater spatial resolution, contrast resolution and temporal resolution. For example, SVGA (super video graphics array) displays might have as many as 1024 by 768 pixels, with 65536 colours and a frame rate of 72 fps.

Digital images are readily archived in electronic form, as discussed in the article on PACS. They can also be relayed by telephone or fibre-optic cable, allowing staff at different sites to view and interact with the images, and contribute to the diagnostic process.

Upgrades and maintenance

A major benefit of a digital system is that the same hardware can be used to perform different tasks, or the same task differently, simply by changing the software. This gives the purchaser some reassurance against obsolescence. Unfortunately, this reassurance cannot be absolute, since hardware changes are also inevitable as new applications and technology are developed.

Reliability has improved with the development of ASICs, since there are fewer connections to fail, and less opportunity for the human and technical faults that can occur when many discrete components have to be assembled. If a fault does develop, on-board diagnostic systems can be interrogated over the telephone by an engineer, pin-pointing the problem and speeding up the repair.

Conclusion

The benefits of digital technology apply from one end the scanner to the other. From beam former to display, they permit substantial advances in image quality, reliability, compactness and value for money. Digital techniques make it possible to practically implement virtually any process that can be expressed in mathematical form, opening up the possibility of a whole new range of valuable features and diagnostic procedures. The digital revolution ranks alongside real-time ultrasound and colour Doppler as a quantum leap in medical ultrasound.

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