

Image Formation and Image Processing in Ultrasound

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Introduction

The range of mechanisms associated with the interaction of ultrasound with biological and other media results in extremely rich encoding of information on echo signals. A substantial amount of the progress in medical ultrasound over the last 30 or so years has been due to the still on-going process of learning how to design the signal and image processing components of scanners so as to best cope with and take advantage of this richness. For example, it is frequently necessary to separate information of different kinds, compensate for interaction between variables, deal with a very wide dynamic range, cope with rather specific kinds of noise, remove artifacts, and display the information in a manner best suited for human observation. Such functions are achieved through appropriate processing that takes place at one or more of a number of the levels indicated in Fig. 1.

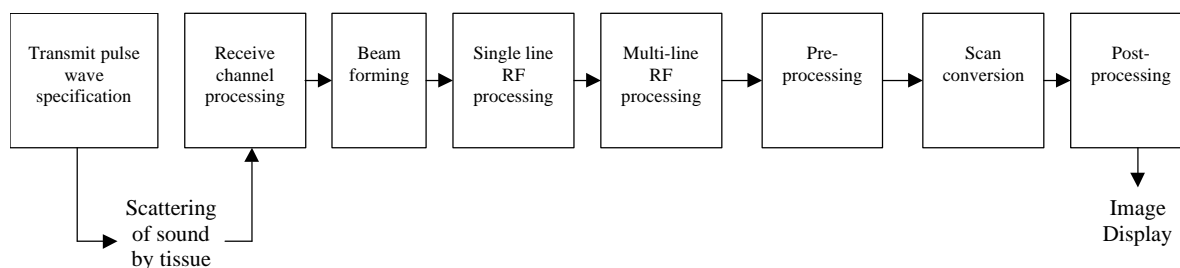


Figure 1. Levels of processing in ultrasonic image formation

This presentation aims to describe both the traditional processing methods and some of the experimental methods currently being explored, at each of these levels. It will be seen, however, that although these divisions help to organise the material for purposes of discussion, they are in some cases somewhat arbitrary. The analogue-to-digital conversion process, which may occur at the channel level or at some other stage following beam forming, although an important aspect of scanner design, will not be discussed.

It is a pleasure to be able to recommend, as an excellent reference for the basics of medical ultrasound image formation, the book that resulted from the last Mayneord-Phillips Summer School, held at St. Edmond Hall, Oxford in 1997. I shall refer to several individual chapters in this book.

Transmit signal processing

The signal processing in an ultrasound scanner begins with the shaping and delaying of the excitation pulses applied to each element of the array to generate a focused, steered and apodized pulsed wave that propagates into the tissue. A good reference for this is Szabo (1998).

Many characteristics of the transmitted acoustic pulse are adjusted in a manner that is linked closely with some adjustment in the received signal processing, the simplest link being the setting of a particular imaging mode. For example, standard pulse shaping includes the length of the pulse that is adjusted for different lines depending on whether the returned echoes are ultimately to be used for contributing to B-scan, pulsed Doppler or colour Doppler imaging modes (Wells, 1998). Equally critical is the centre frequency of the pulse, which, for modern broadband transducers, can be set over a wide range and according to the part of the body being scanned. This is, for signal-to-noise and other reasons (see later), frequently linked to a band-pass filter on the receive side. On some scanners the peak acoustic pressure of the transmitted pulse is linked to the overall receiver gain so that changes to acoustic output made in association with safety judgements affect the depth of penetration (because of the altered signal-to-noise ratio) but not the overall image brightness.

A number of scanners also routinely shape the envelope of the pulse (for example, to be Gaussian in shape) to improve the propagation characteristics of the resulting sound wave. Various experimental approaches to shaping the transmit pulse have also been explored specifically with pulse coding in mind, to improve the pulse time-bandwidth product as a

means of increasing SNR without increasing peak acoustic pressure, or to overcome the limitation on data acquisition rate imposed by the speed of sound.

New reasons for shaping transmit pulses have recently come about through the wish to improve imaging of gas microbubble-based ultrasound contrast media (Cosgrove, 1998). These aim to take advantage of the inherent non-linearity of the scattering from gaseous inclusions and one example is to alternately transmit pulses that are 180 phase inverted. Once again this must be linked to appropriate processing in the receiver to take advantage of the new information potentially generated by using such pulses. Other examples involve limiting the bandwidth of the transmitted pulse so that receive filtering can detect the non-linear generation of harmonics in the echo signal, and variation in peak pulse pressure so that non-linear variations in echo amplitude may be detected.

Receive channel level processing

Echoes resulting from scattering of the sound by tissue structures are received by all elements within the transducer array. Processing of these echo signals routinely begins at the individual channel (element) level with the application of apodization functions, dynamic focusing or steering delays, and mix-down processing (for some older scanners) to reduce the cost of the former. Knowledge of the speed of sound is important here. Conversely in some experimental scanners repeated guesses were made for the average sound speed and some measure of image sharpness was used as a means of estimating the sound speed in the medium. This property is not usually extracted in routine use of ultrasound scanners but was found to be useful for some diagnostic problems.

Other experimental systems attempt to apply phase aberration correction, aiming to improve the spatial resolution, contrast and/or SNR that suffer from the wave-distorting effects of propagating through inhomogeneous media and of incoherent scattering structures. Methods studied for deriving the correction functions have thus far included use of image-derived geometrical information combined with knowledge of sound speeds, channel level iterative phase adjustment algorithms that employ cost functions involving speckle brightness or measures of coherence between channels, and so-called time reversal.

Channel level signal processing has also been investigated as a means of removing acoustical clutter signals. One example of this is the so-called velocity-guided median filtering method, taken from ideas employed in seismological acoustical signal processing.

Beam forming

This is the process by which the signals on separate channels, each received from a different transducer element, are combined to form a single signal representative of the echoes received from the tissues by the defined transducer aperture. Both analogue and digital beam formers are still in use although the latter are rapidly gaining dominance as their cost decreases, due to their greater flexibility and precision. Szabo (1998) also discusses beam forming. Aperture subdivision and partially coherent beam forming improves the speckle and other SNR, at the expense of spatial resolution but with net benefit to low-contrast lesion detectability. Signal to noise ratio considerations in ultrasound imaging are somewhat unique to the modality and are worth of individual discussion (Hill, 1998).

Single line RF processing

Echo signals corresponding to individual beam-formed lines are processed using a very wide variety of techniques, for a wide range of objectives. Frequency demodulation and other methods used to extract blood flow information, and to create colour flow images, represent a large and important subject (Wells, 1998).

All ultrasound scanners amplify the echo signals and compensate for attenuation losses. Low noise pre-amplifiers are necessary to maximize penetration at a given operating frequency. Applying some of the amplification before beam forming takes advantage of the noise averaging properties of the beam forming process. Swept gain, or TGC (time-gain-compensation), is applied to compensate for changes in echo signal strength with depth. These may be due to attenuation loss or diffraction loss (or gain). There is a range of commercially implemented and experimental systems for automatically adjusting swept gain functions. The simplest is probably a pre-set TGC function based on knowledge of the average image properties for the probe connected to the system. More complex systems continuously estimate the attenuation coefficient by analysing the backscattered signal properties.

Noise reduction and other benefits are achieved by band-pass filtering that is linked to the centre frequency and bandwidth of the transmitted pulse. Dynamic adjustment of the centre frequency of this filter has been used both in an attempt to correct for the downshift in centre frequency of a pulse as it propagates and to track this downshift. The former attempts to maintain consistent spatial resolution and image appearance with depth whilst the latter strategy aims to maximize SNR at all depths. Filtering is also used, as mentioned earlier, to detect in the echo signal the presence of harmonics of the transmitted centre frequency. Such

harmonics may arise in the transmitted beam as it propagates nonlinearly (Baker, 1998) or may come from non-linear acoustic scattering by microbubble ultrasound contrast media (Cosgrove, 1998). The former has resulted in improved imaging of tissues without contrast media but when propagating through reverberation and aberration-inducing media, whilst the latter has brought about improved signal to clutter ratio in the detection of microbubble contrast media.

Echo-line signal averaging, for two or more pulses launched down the same line-of-sight, has also been employed to improve SNR at the expense of frame rate. Parallel beam forming systems are capable of mitigating this compromise to some extent.

The later stages of conventional signal processing also always include some form of dynamic range compression (such as logarithmic amplification), edge enhancement and demodulation to detect the envelope of the echo signal. Final signal conditioning may also include an adjustable threshold rejection of low-level echoes and noise. These options are also known as “pre-processing” functions and there are frequently a number of compression characteristics and edge enhancement settings that the operator may choose from.

A very wide range of experimental processing methods has been explored that operate at the individual line level, most aiming to extract new information. Examples include algorithms to measure:

- (a) the average attenuation coefficient and its frequency dependence (either from frequency downshifts or from echo decay with depth),
- (b) properties such as scatterer size, from the frequency dependence of the scattering coefficient,
- (c) the cyclic variation of “integrated backscatter” from myocardium, and
- (d) tissue elasticity information by tracking the displacements induced by some external force.

Speckle noise reduction has also been applied at this level, both using frequency compounding and using algorithms that aim to estimate the envelope of the echo signal that would have existed had destructive interference not occurred.

Multi-line RF processing

A variation on the theme of automatic swept gain is the “lateral gain” applied in some instruments to compensate for different amounts of attenuation associated with different propagation paths.

In some systems multiple RF lines are buffered and additional processing is applied, prior to demodulation. For example, interpolation between RF lines before any non-linear signal processing is applied improves image quality and helps to reduce the risk of aliasing in the lateral direction. Further use is also made of information contained in the phase relationship of echoes between adjacent lines. The processing involved may be likened to that of a “second stage” of beam forming and many implementations of this type of processing are, in principle, possible. This may well be the pre-cursor to the idea of demodulating after scan conversion, or the beginnings of an evolution towards synthetic aperture imaging.

Scan conversion

This is traditionally the stage at which interpolation between envelope-detected signal lines occurs, to determine the echo amplitude values that must be written to a display memory whose read-out is in rectangular co-ordinates, even though the echo lines may have been collected in a polar (or other) co-ordinate system. Various algorithms have been explored and it remains an important determinant of final displayed image quality. If three-dimensional scanning has been carried out, for example by moving a linear array, then the scan conversion process involves three dimensional interpolation. The sampling of such data is often highly non-uniform, irregular and anisotropic and suitable algorithms are still being explored.

At this stage it is possible also to apply "multi-line envelope processing" for tasks such as angle compounding (which enhances speckle SNR, reduces shadow artefacts and improves outlining of smooth interfaces) and creating a mosaic of images to extend the field of view in a lateral direction.

Post-processing

The processing that occurs following interpolation and scan conversion conventionally includes such functions as assigning a user-selectable look-up-table that translates echo amplitude values to display brightness or colour. Careful choice of this setting is important for full transfer of the displayed information to human observers, and it strongly interacts with control of ambient lighting. This is also the stage at which different kinds of information (such as B-mode and colour Doppler) are combined for simultaneous display.

Frame averaging (persistence) is often provided as a means to interactively improve contrast discrimination by speckle reduction, but at the expense of motion degradation of spatial resolution. Substantial spatial or temporal smoothing of colour Doppler displays is frequently employed to improve the appearance of the relatively small number of lines that can be acquired if a high frame rate is required, as in cardiological applications.

Experimental systems for speckle reduction have been applied at this level, employing adaptive spatial or temporal filtering, yielding worthwhile results but requiring compensation for all of the preceding stages of signal processing. Attempts to extract new information at this stage, for example via image texture analysis, also suffer from this problem but have been quite successful in some cases. A form of adaptive contrast or texture enhancement has begun to appear on the market. It is not entirely clear how this operates but almost certainly does so at more than one level in the processing chain.

Automatic boundary detection has been applied only to a limited extent in commercial scanners although the literature abounds with experimental approaches, some of which are beginning to look promising for specific applications.

Finally, image densitometry methods have been developed for both grey scale and colour Doppler images and are finding increasing application in areas such as monitoring the time-varying concentration of contrast agents.

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Image Formation. • The two parts of the image formation process. The geometry of image formation which determines where in the image plane the projection of a point in the scene will be located. The physics of light which determines the brightness of a point in the image plane as a function of illumination and surface properties. • A simple model. - The scene is illuminated by a single source. • the image sharpness is limited by diffraction. * when light passes through a small aperture, it does not travel in a straight line. * it is scattered in many direction (this is a quantum effect). - In general, the aim of using lens is to duplicate the pinhole geometry without resort-ing to undesirable small apertures.