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## MEDICAL ULTRASOUND IMAGING USING PULSE COMPRESSION

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Pulse compression techniques can play a major role in improving image quality in medical ultrasound. A prototype imaging and digital signal processing system incorporating this technique is described. Feasibility studies were performed and system resolution was evaluated with experiments on tissue mimicking phantoms.

In conventional medical ultrasound, peak acoustic intensity, rather than time average intensity, of the interrogating ultrasound pulse limits the signal-to-noise ratio (SNR) and

maximum penetration depth. Furthermore, attenuation of ultrasound in soft tissue increases with frequency, setting an upper limit of usable frequency at about 7 MHz. However, better resolution and contrast can be achieved if imaging can be performed at higher frequencies. Within the framework of short duration (few  $\mu\text{s}$ ) pulses used in medical ultrasound it is generally not possible to achieve these desirable improvements without increasing peak intensities significantly above the current levels. Such an option may not be advisable because of a possible increase in cavitation mediated bioeffects. This dilemma can only be resolved using coded excitation pulses and pulse compression techniques. Such techniques have been used extensively in radar systems [1]. A major aim of this Letter is to demonstrate the feasibility of this technique in medical ultrasound by performing experiments on tissue mimicking phantoms.

The point spread function (PSF) and the resolution of a conventional B-scan imaging system is generally well understood. It is not obvious whether similar resolution can be achieved with a pulse compression based imaging system. The second aim of this Letter is to show that resolution (axial and lateral) similar to that of conventional B-scan is possible with this technique along with a concomitant increase in SNR.

The linear frequency modulated (FM) pulse coding considered here is one form of pulse coding among many others. Although dispersive delay lines have been used to perform pulse compression, crosscorrelation processing is another viable alternative. In such systems the time-bandwidth product is an indicator of the achievable SNR improvement. We have shown through system modelling and simulation that in medical ultrasound, unlike radar, frequency dependent attenuation in soft tissue will limit the attainment of a large time-bandwidth product of the order of 10 to 40 is possible under normal operating conditions. For example, in the present study a  $20\ \mu\text{s}$  FM pulse with an effective bandwidth of 1 MHz is capable of improving the SNR by a factor of about 20. It is important to note that this factor is not constant for the entire image but changes with depth in medical ultrasound. A detailed theoretical analysis of this issue was presented elsewhere and will not be considered here further [2]. We will concentrate on the issue of experimental evaluation of PSF [3].

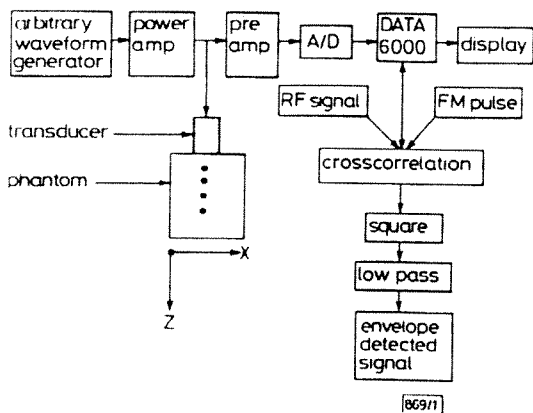


Fig. 1 Experimental setup

Fig. 1 shows the experimental setup. An arbitrary waveform generator was programmed to generate a  $20\ \mu\text{s}$  linearly swept frequency modulated (FM) pulse with a centre frequency of 2.4 MHz and a 6 dB bandwidth of 1 MHz. A raised cosine window function over the  $20\ \mu\text{s}$  period was used to reduce sidelobes in pulse compression processing. A Panametric unfocused piezoelectric circular disk transducer was used to transmit the FM pulse into the phantom. The transducer had a diameter of 1.27 cm. It had a centre frequency of 2.4 MHz and a 6 dB bandwidth of about 1.8 MHz. The beginning of the far-field, defined by the last maxima along the transducer axis was located at approximately 9 cm in water, when the transducer was operated at 2.4 MHz. The backscattered RF signal, after amplification was digitised by Analogic DATA 6000 at 50 MHz with 8 bit resolution. 8192 data points covering about 12.6 cm depth ( $163\ \mu\text{s}$ ) were stored in the memory for every

line. The transducer was moved laterally along the x-axis at 1 mm intervals in order to collect 28 difference lines of RF signal. The FM pulse used to drive the transducer was also digitised and stored for pulse compression processing.

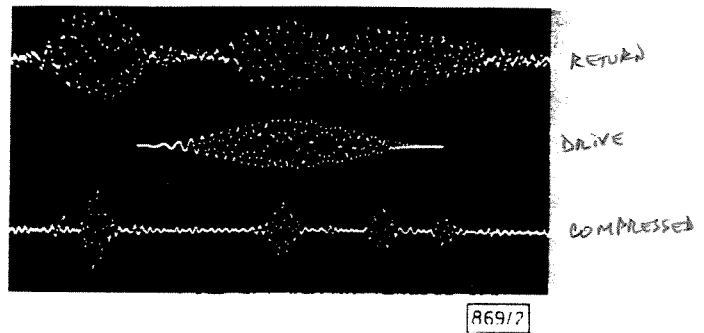


Fig. 2 Digital crosscorrelation processing

Processing: All the processing steps illustrated in Fig. 1 were carried out digitally on DATA 6000. Fig. 2 illustrates the concept of pulse compression processing. The middle trace is the FM pulse that drives the transducer. The top trace is the backscattered signal received from four wire targets at different depths. The bottom trace is the RF signal after crosscorrelation processing with the input FM pulse. Note that the four targets are fully resolved after pulse compression processing. Fig. 3 shows one example of processing in two dimensions. Fig. 3a is a grey scale two-dimensional plot of the backscattered RF signal from one wire target at a depth of 9.1 cm. The horizontal axis represents time (or depth  $z$ ) and the vertical axis represents the transverse or scanning direction (x-axis in Fig. 1). The Figure is essentially a collective display of 28 lines of RF signals. It is interesting to note that as the target moves (as a result of transducer scanning in the x-direction) to either side of the transducer axis, the nature of the RF signal changes. The signal is not only decreasing in amplitude, its frequency spectrum is also changing. The higher frequencies are lost or removed from the beam more efficiently than the lower frequencies. This is due to the fact that the diffraction pattern depends on the wave frequency. To facilitate pipeline processing a scheme was adopted whereby every line of the RF signal was crosscorrelated with the *same* input FM pulse. The FM pulse used for crosscorrelation, therefore, is not optimally matched to reflection from any particular depth, it is simply the FM pulse that was input to the transducer. Fig. 3b shows the two-dimensional grey scale image after such crosscorrelation processing. Finally, every line after crosscorrelation processing was envelope detected, and the final B-scan image is shown in Fig. 3c. This, by definition, is the point spread function (PSF) of the FM pulse imaging scheme. Just as in conventional short pulse imaging, the PSF is *shift-variant*. It depends on the depth range from the transducer, and also on the FM pulse parameters, i.e. centre frequency and bandwidth.

Results: We now present results of imaging performed on a tissue mimicking phantom. The phantom had tissue equiva-

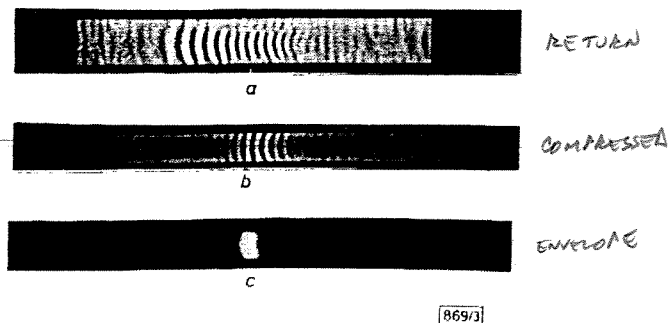
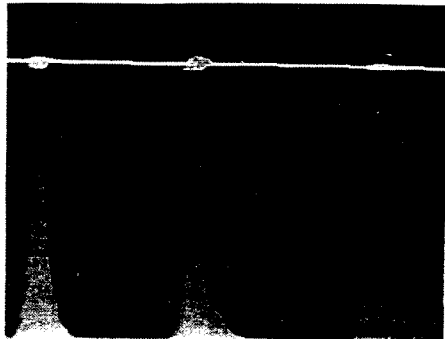


Fig. 3 Processing in two dimensions

- a RF signal
- b After pulse compression processing
- c After envelope detection and low pass filtering

lent material with a linear attenuation coefficient  $\alpha_0 = 0.15$  dB/cm/MHz. Steel wires were imaged as scattering targets located at three different depths,  $z_0 = 3.1$  cm, 5.1 cm and 9.1 cm. The distances were chosen such that the three scatterers are approximately in the near field, the transition zone and the far field of the transducer, respectively. Fig. 4 shows the B-scan image of the three scatterers after pulse compression processing. The axial profiles of the point spread functions along the transducer axis are also shown as a one-dimensional plot. The 6 dB width of these profiles, defined as the axial resolution, was around  $1.3 \mu\text{s}$  ( $\approx 0.5$  mm). A short pulse with similar bandwidth produced similar results.



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Fig. 4 PSF of FM pulse imaging scheme

Resolution in the lateral direction is expected to be controlled by the diffraction pattern of the transducer. Because these patterns are complex in the near field and transition zone, the lateral profiles (not shown) were also found to be complex, with several maxima and minima. For the scatterer in the far field, an approximate analysis of the lateral profile can be

performed. The theoretically expected pattern has an approximate 6 dB width given by  $(\lambda \cdot z)/d$ , where  $\lambda$  is the wavelength at the centre frequency,  $z$  is the distance to the scatterer and  $d$  is the transducer diameter [4]. For our system we expect a value of 5.2 mm. The lateral profile was measured and the 6 dB width was found to be 4.3 mm. Our analysis of the PSF shows that the observed axial and lateral resolutions are within 20% of what we expect from conventional short pulse imaging.

In summary we have presented preliminary results on a prototype imaging scheme for medical ultrasound that uses a pulse compression technique. The system considered could produce SNR enhancement by a factor of 20. The point spread function was experimentally evaluated and found to be consistent with conventional B-scan imaging. Further optimisation and exploitation of SNR enhancement for higher frequency operation is under investigation.

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