Phys. Med. Biol. **43** (1998) 455–465. Printed in the UK PII: S0031-9155(98)80314-X

A new imaging science test object for performance measurements of ultrasonic imaging systems

Dan Phillips and Kevin J Parker

Rochester Center for Biomedical Ultrasound, Department of Electrical Engineering, University of Rochester, Rochester, NY 14627, USA

Received 2 December 1996, in final form 1 August 1997

Abstract. We propose a novel test object for ultrasound imaging. The test object, or phantom, is manufactured using thin film techniques allowing precise placement of 'digital scatterers' which can produce sophisticated test targets, similar to those that are widely used in imaging science to evaluate displays, printers and electronic imaging systems. These test objects can be used in conjunction with standard performance evaluation methods and devices to augment and enhance their capabilities and range of application.

1. Introduction

The image displayed by an ultrasound scanner is the result of many complex stages and operations. Extensive signal processing is involved in both the transmitted and received signals. When such sophisticated systems form the basis for medical diagnosis and treatment, techniques for comprehensive yet manageable performance evaluation are essential.

There are generally two components necessary for an effective performance evaluation procedure: (i) standard test objects and (ii) methods to evaluate how well the system under consideration measures or images the test objects.

In medical ultrasonic imaging, test objects have typically consisted of an assemblage of target items embedded in some type of material with varying acoustic propagating properties (AIUM 1991). Methods to assess system performance have included characterization of spatial resolution and accuracy as well as discrimination of varying acoustic properties. Various phantoms have produced 'lesions' of different size and echogenicity for lesion detection study (AIUM 1991, ATS Laboratories 1993, Cone Instruments 1993, Madsen *et al* 1978, 1980, Sommer *et al* 1980, Yao *et al* 1991, Alasaarela and Koivukangas 1990, Spitzer *et al* 1979, Smith 1982, Goldstein and Clayman 1983). Other random scatterer regions have been used to assess the beamwidth of an ultrasound transducer (Ophir *et al* 1983). As in imaging science, line and point targets can be added to a background to make basic measurements of distortion and point spread functions (Rose and Weimer 1989, Dainty and Shaw 1974, Carlson 1977).

It has long been recognized (Hill and Kratochwil 1981, Goldstein and Clayman 1983) that methods from the discipline of imaging science should provide valuable information regarding the overall performance of an ultrasound imaging system. Evidence for the continued need for this type of approach is given in the award-winning paper by Hill *et al* entitled 'What might echography learn from image science' (Hill *et al* 1991).

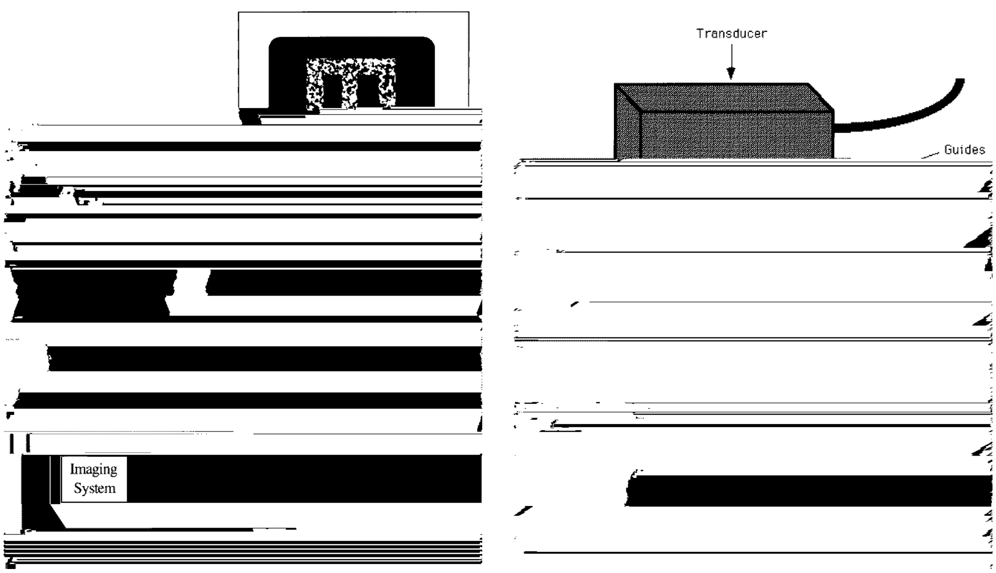
0031-9155/98/020455+11$19.50

Standard imaging science measurements can be difficult to obtain with conventional ultrasound test objects such as cones, spheres and wires of varying echogenicity. We demonstrate a new class of ultrasound imaging test objects that can be manufactured with precise control of the echogenicity of the target patterns. The requirements for constructing such targets for ultrasound imaging include precise distribution of scatterers on a surface of one or more thin film substrates with control over the local concentration and distribution of the scatterers. This approach is described in the next section.

2. A thin film test object with digital scatterers

2.1. Thin film propagation

The test object is constructed with a flat substrate supporting a spatial test pattern of 'digital scatterers' produced by an appropriate thin film deposition technique. The thin film test object is then oriented coplanar to the scanning plane of the ultrasonic imaging system being evaluated. Assuming that the substrate thickness is much less than a wavelength of the ultrasound pulse, the pulse will propagate at close to the speed of sound of the host medium (Archer-Hall and Hutchins 1979, 1981), and the acoustic inhomogeneities presented by the deposited pattern will produce reflected waves that will be detected and processed by the ultrasound scanner (see figure 1(*a*)).



(*a*) (*b*)

Figure 1. (*a*) Schematic diagram of the concept of a thin film test object. (*b*) Representation of a simple implementation of a phantom incorporating a thin film test object.

In essence, this technique allows a very controlled volume distribution of scatterers, albeit in a volume of minimal thickness. In this manner, the volume distribution of the scatterers is tightly controlled in two ways: in the 2D scanning plane, the scatterer dimensions are specified by the resolution of the deposited pattern; in the out-of-plane direction of the interrogating beam, the scatterer dimension is determined by the thickness of the deposited pattern.

2.2. Scattering

Acoustic scattering results from spatial variations in the acoustic impedance of the insonated material (Morse and Uno 1986). The three acoustic impedances of interest in this case are those of the propagating medium, the test object substrate and the material deposited on the substrate that forms the thin film pattern used for evaluation. Since this test object is to be used for evaluation of medical ultrasound scanners, the propagating medium is normally assumed to have an acoustic impedance close to that of tissue and an attenuation of 0.3 to 1:0 dB cm ^{1} MHz ^{1} as suggested by the AIUM guidelines (AIUM 1991). The substrate material's acoustic properties need not exactly match those of the propagating medium as long as the material has smooth surfaces and has a thickness on the order of, or less than, the ultrasound wavelength. Finally, the material comprising the deposited scatterers must have an acoustic impedance that is detectably different from that of the propagating medium. As shown in figure 1(*a*), the scatterers are deposited as a thin film on a substrate which

propagating medium) and have the capacity to be deposited in a uniform film, in terms of both material properties and thickness.

A substrate such as glass or even quartz might lend itself to these techniques, and would certainly remain stable when immersed in an aqueous solution. However, both substances have a significantly different acoustic impedance with respect to water ($Z_{\mathrm{water}} = 1.48 \times 10^6$ Pa s m^{-1}, $Z_{\mathrm{glass\,(Pyrex;bar)}} = 12.0 \times 10^6$ Pa s m^{-1}, $Z_{\mathrm{quartz\,(X\text{-}cut;bar)}} = 14.5 \times 10^6$ Pa s m^{-1} (Kinsler *et al* 1982)). A nylon, polystyrene or Lucite substrate with an acoustic impedance more closely matched to water ($Z_{\mathrm{nylon\,(6\text{-}6;bar)}} = 2.00 \times 10^6$ Pa s m^{-1}, $Z_{\mathrm{polystyrene\,(bar)}} = 2.37 \times 10^6$ Pa s m^{-1}, $Z_{\mathrm{Lucite\,(bar)}} = 2.15 \times 10^6$ Pa s m^{-1} (Kinsler *et al* 1982, Weast 1969)) lends itself more favourably to less expensive procedures such as lithography and electrostatic printing.

3. Methods

Due to readily available, low cost and well developed computer interfaces for pattern transfer via laser printing, initial test objects were generated using 300 and 600 dpi laser printers. Some of the patterns were first printed on common 20 lb copier paper and then transferred to Kodak Ektaprint Transparency Material (Cat 151 4793) using a Kodak Ektaprint Model 225 copier–duplicator system (Kodak, Rochester, NY). Some of the patterns were printed directly on to the transparency material with a DEClaser 1152 300 dpi laser printer (Digital Equipment Corporation, Boston, MA).

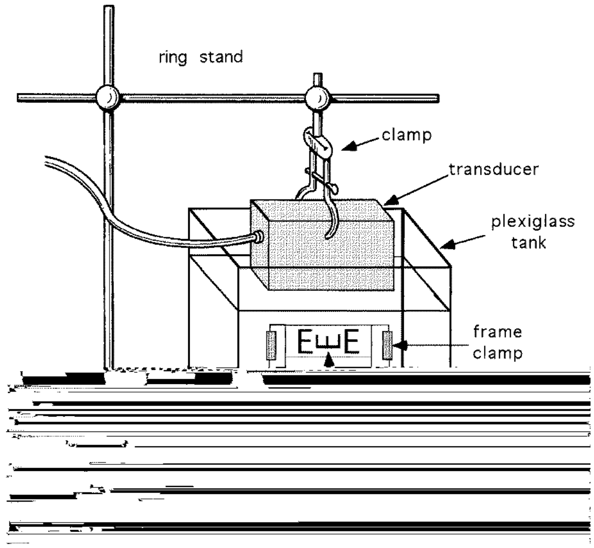


Figure 3. Experimental configuration.

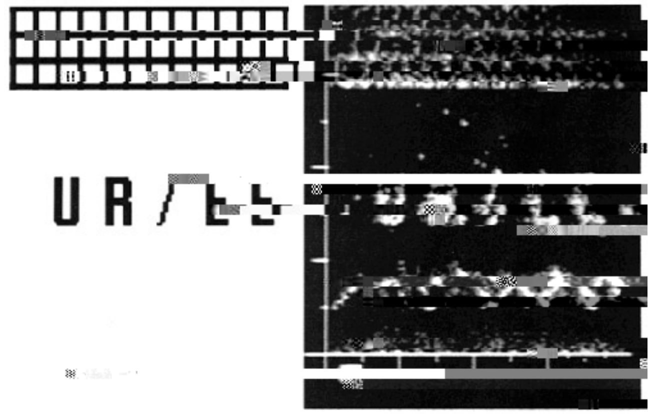
4. Results

To facilitate initial evaluation, relatively straightforward patterns consisting of lines, dots and upper case alphanumerics were used (figures 4(*a*) and 4(*b*)). A more complex circular grid exhibits a degradation of resolution in the diverging field beyond the focal zone (figure 4(*c*)). A gray scale pattern was imaged as a test of half-tone techniques (figure 2).

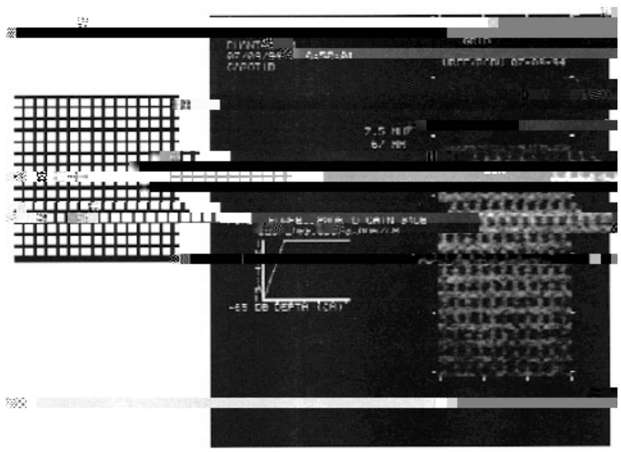
Figure 2 consists of a pattern generated utilizing the Blue Noise Mask. The level corresponds to the number of printed or dark dots in a given area of interest out of a maximum of 256. The test pattern was produced on a 300 dpi printer with each printed dot having a height and width of approximately 85 m. The grids shown in figures 4(*a*) and 4(*b*) consist of 0.8 mm thick lines with a spacing of 2.4 mm. Since the targets were immersed in water, in which sound has a lower speed than in tissue (1490 m s ^{1} versus 1540 m s ^{1}), the vertical aspect of the image appears slightly elongated. This is also evident in figure 4(*c*), which is an image of a circular grid pattern of 0.3 mm thick lines. The grid has an overall diameter of 51 mm and inner circles with radii measuring 6.35 mm, 12.7 mm and 19.05 mm.

Figures 2, 4(*a*) and 4(*c*) were obtained with the Acuson 128/XP10 utilizing an L738 7 MHz linear array transducer. Figure 4(*b*) was obtained with the Quantum QAD-1 using a 7.5 MHz linear array transducer.

[illegible]



(*a*)

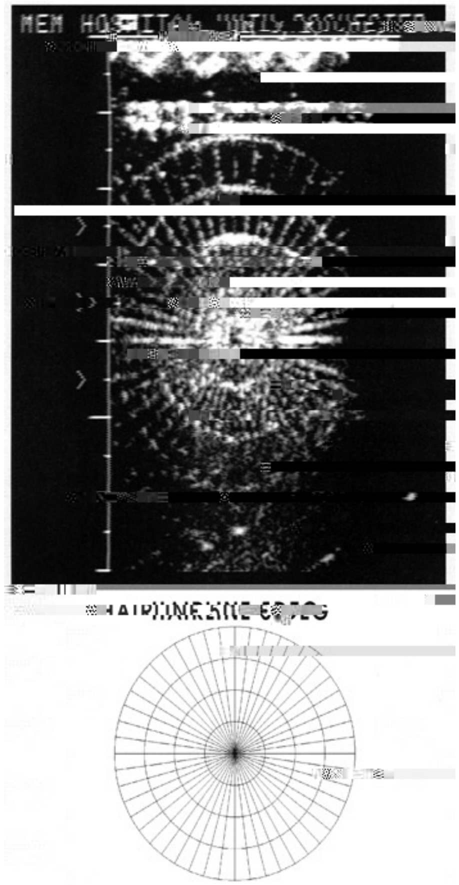


(*b*)

Figure 4. (*a*) Example of Acuson 128XP scan, 7 MHz transducer; the original pattern used to produce thin film is on the left. (*b*) Example of Quantum QAD-1 scan, 7.5 MHz transducer; original pattern on the left. (*c*) Example of Acuson 128XP scan, 7 MHz transducer; the original pattern used to produce the thin film is below.

7.5 MHz; displayed brightness assessed using green tag function in continuous mode). The images were digitally captured and redisplayed on a high-quality JVC TM-1400SU (Victor Company of Japan, Yokohama, Japan) video monitor to facilitate scoring. Five observers visually compared the displayed images and were asked to count the number of lines they could resolve in the four quadrants of the pattern up to the smallest line they could resolve. Accuracy and reproducibility is limited by the quantization of the line widths and intraobserver variability. In the experiment, line widths ranged from 0.2 mm to 1.8 mm (2.5 lines/mm to 0.28 lines/mm). Figure 5 shows the line pair test pattern and the images produced from the scans at 5 MHz and 7.5 MHz. Table 1 shows the results of the five test subjects who evaluated the images.

As would be expected, resolution of the horizontal lines by the 7.5 MHz transducer was superior to the 5 MHz transducer. Resolution of the vertical lines was approximately the same, although there was a higher variation of the observations obtained from the 7.5 MHz



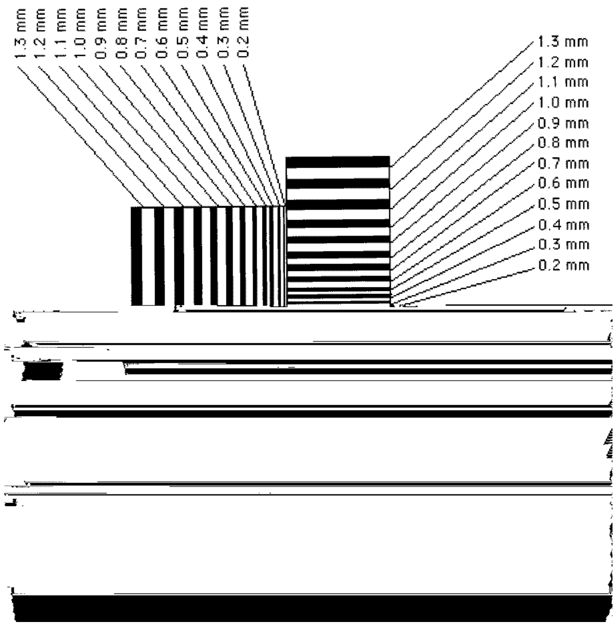
(*c*)

Figure 4. (Continued)

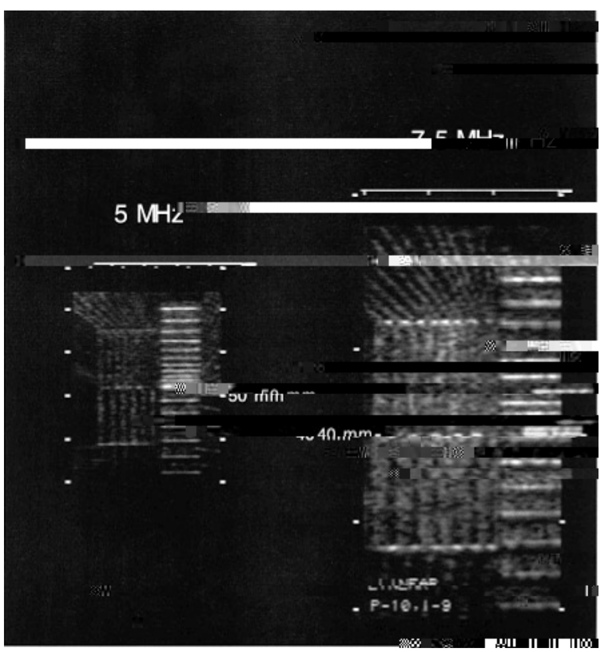
image. The manufacturer's specifications for the 6:0 dB image resolutions in tissue were 0.26 mm (axial) and 0.8 mm (lateral) for the 7.5 MHz transducer and 0.38 mm (axial) and 1.4 mm (lateral) for the 5 MHz transducer.

5. Discussion

The thin film test object incorporating digital scatterers makes possible new and useful imaging test patterns. As such, it may find utility in endeavours ranging from basic system performance investigation to routine quality assurance tasks. In fact, the thin film test object under consideration could be implemented in a number of ways for general-purpose quality-assurance use. For the sake of conciseness, we will focus333(of)9gss,ie,4sjo33(werance)s2(of63(will)-333(focuse.)-44412asic)-31412



(*a*)



(*b*)

Figure 5. (*a*) Resolution experiment target pattern. Line widths are as indicated. (*b*) Resolution experiment images. Images acquired with an Quantum QAD-1 scanner utilizing linear array transducers operating at 5 MHz (left) and 7.5 MHz (right). Images are displayed in same proportion as on the scanner display. Horizontal and vertical distance markers represent 10 mm increments. 5 MHz settings: slope 0 dB cm ^{1}, power 10 dB, initial 10 dB. 7.5 MHz settings: slope 0 dB cm ^{1}, power 10 dB, initial 9 dB.

Table 1. Results of the line pair resolution experiment based on observations of five subjects. Horizontal refers to horizontal (aligned with azimuthal axis) lines, vertical refers to vertical (aligned with depth axis) lines. Mean widths for the smallest line resolved are rounded to the nearest 0.1 mm and mean spatial frequencies are rounded to the nearest 0.1 line pair (lp) per millimetre. SD: standard deviation.

Smallest resolvable line width

The variety of complex patterns it affords can enable multiple image analysis measurements to be performed from the scan of a single test object. Further, these test objects may be easily incorporated into currently used ultrasound imaging phantoms to add to their recognized test capabilities and overall utility.

References

AIUM 1991 *Standard Methods for Measuring Performance of Pulse-Echo Ultrasound Imaging Equipment* (Rockville, MD: American Institute of Ultrasound in Medicine)

Alasaarela E and Koivukangas J 1990 Evaluation of image quality of ultrasound scanners in medical diagnosis *J. Ultrasound Med.* **9** 23–34

Archer-Hall J A and Hutchins D A 1979 The photoelastic visualization of ultrasonic waves in liquid *Ultrasonics* September 209–12

——1981 The effectiveness of thin layers as ultrasonic visualization media *Ultrasonics*