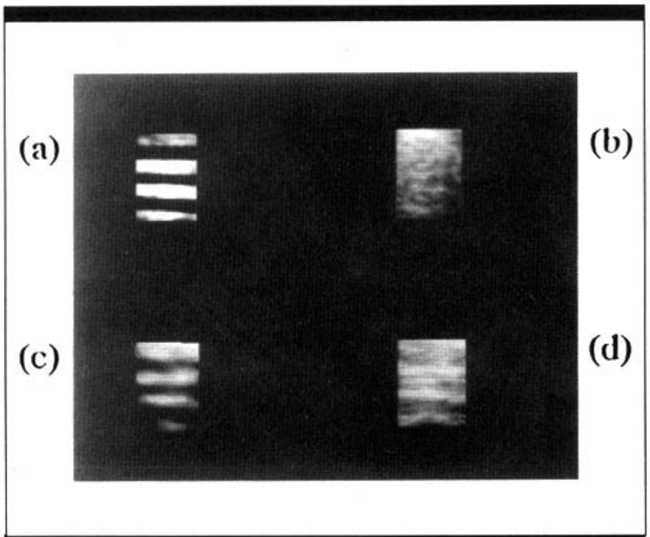

2-D IMAGES OF TEST CHART BEHIND A 3.5 MM THICK HUMAN BREAST TISSUE ILLUMINATED BY 8 PS 530 NM LASER PULSES. TEST OBJECT IS A 5 LINE PAIRS/MM TARGET FROM AN AIR FORCE BAR TEST CHART. DARK BARS ARE THE OBJECT AND WHITE AREA IS THE TRANSPARENT BACKGROUND. THE WIDTH OF EACH BAR IS ~100 μM. PART OF THE IMAGE NON-UNIFORMITY CAN BE ACCOUNTED FOR BY THE LASER BEAM NON-UNIFORMITY AND THE SAMPLE: REFRACTIVE INDEX VARIATION AND INTERNAL STRUCTURES. (a) REFERENCE IMAGE (TISSUE REMOVED); (b) NO TIME GATE (STANDARD TRANSILLUMINATION) (c) T_D=0, TIME GATE AT ZERO DELAY TIME; (d) T_D=22-PS, TIME GATE AT 22-PS DELAY TIME.

mm thick breast, one estimates the need of shorter pulses ~1 ps for the gate. In addition, a cooled CCD detector, a high repetition rate multiple pulses, and a multi-stage cascade time gate can increase the S/N by an additional factor of 10^8. It is estimated that 2D low-level signal images with an attenuation factor of e^{-28} through a scattering wall can be obtained. This makes time-gate imaging technique viable for the future optical mammography and tomography.

References

1. L. Wang *et al.*, "Ballistic 2-D imaging through scattering walls using an ultrafast Kerr gate," Science **253**, 1991, 769-771.
2. J.G. Fujimoto, "Femtosecond optical ranging in biological systems," Opt. Lett., **11**, 1986, 150-152.
3. G. Navarro and A. Profio, "Contrast in diaphanography of the breast," Med. Phys. **15**, 1990, 181-187.
4. K.M. Yoo and R.R. Alfano, "Time-resolved coherent and incoherent components of forward light scattering in random media," Opt. Lett. **15**, 1990, 320-322.
5. B. Chance, ed., *Photon Migration in Tissues*, Plenum Press, New York, N.Y., 1990.
6. M.A. Duguay and A.T. Mattick, "Ultrahigh speed photography of picosecond light pulses and echoes," Appl. Opt. **10**, 1971, 2162-2170.
7. K. Spears *et al.*, "Chrono-coherent imaging for medicine," IEEE Trans. Biomedical Eng. **36**, 1989, 1210-1221.
8. H. Chen *et al.*, "2-D imaging through diffusive media using gated electronic holographic techniques," Opt. Lett. **16**, 1991, 487-489.

Electronic Holography for Imaging Through Tissue Using Femtosecond Gated Pulses

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Imaging through and into highly scattering media is a major problem of optics. One potential application is for medical imaging—to see through biological tissue. One imaging method uses short pulses (picosecond or subpicosecond) and the principle of the first arriving light.[1] Here, a short pulse of light enters the medium and emerges as a greatly elongated pulse. The light that is scattered least emerges first, and the more scattered light emerges later. The least scattered light, being distorted the least, will form the best image of any absorbers located behind or embedded within the material. Gating methods are then used to separate this first arriving light from the rest.

A wide range of different methods have been used or proposed. Holography is one of the methods. As carried out by Abramson, Bjelkhagen, and Spears,[2] a hologram is made of the scattered light, using very short pulses (or equivalently, a short coherence light source) and the reference beam path delay is adjusted so that the reference beam interferes only with the first arriving light. This is the basis of their Chrono-coherent process. Others, including Alfano and his group at The City College of New York, have used other methods.

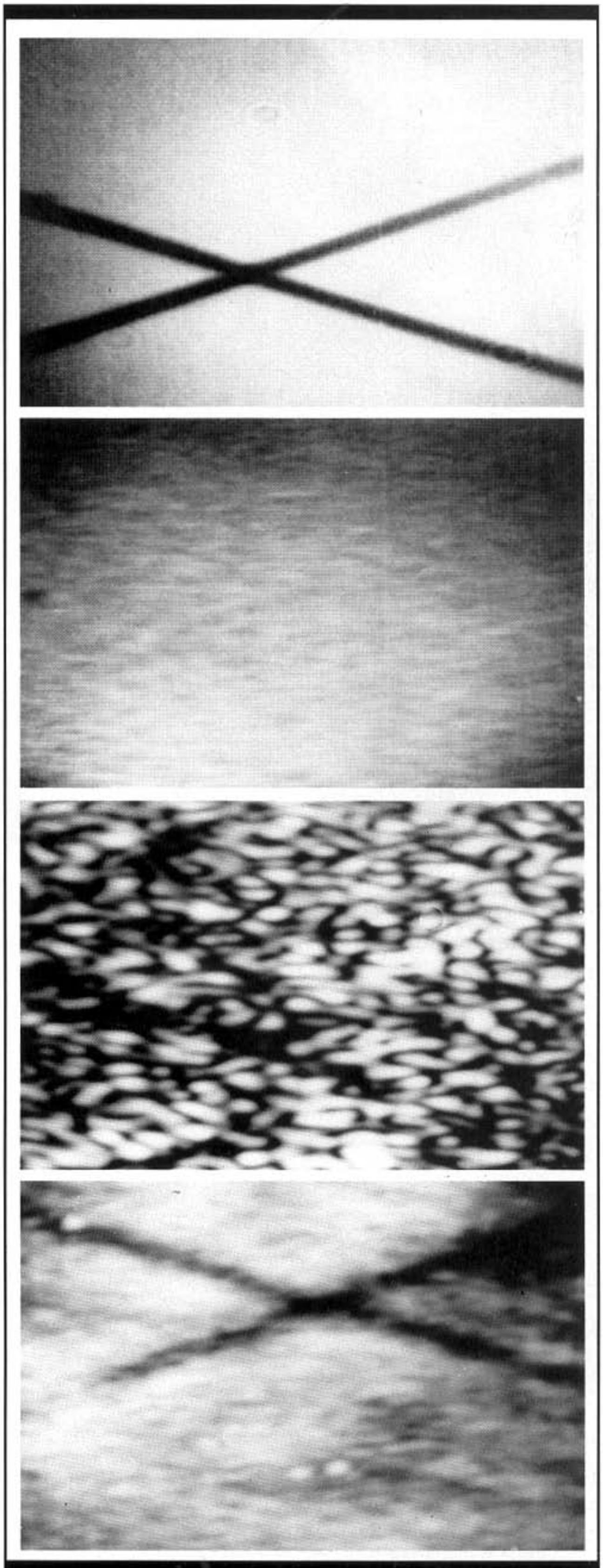
We have combined the holographic method with electronic holography, which avoids some of the limitations of conventional holography and is uniquely matched to the present problem.[3] We form the hologram on the detector of a cooled CCD camera.

The diffusing medium may be inherently stable, as with most solids, or unstable, as with living tissue. To make a hologram of an unstable object requires a pulse laser, where the total light needed for the exposure is delivered in a short time, perhaps about a ms. This can pose a problem, since inconveniently high light levels could be required. A second problem is that, for several reasons, the image will be noisy. First, the later arriving light, which does not interfere with the reference beam, nonetheless exposes the hologram as an ambient background, adding noise and reducing fringe contrast. Also, the image will have considerable speckle because of the scattering medium.

The problem of the short stability time is avoided with electronic holography. The exposure time of each hologram can be shorter than the stability time of the medium. The resulting hologram may produce a very weak and noisy image, but no matter; the process is repeated many times, with the time intervals much greater than the stability time. Thus, the speckle pattern on the different reconstructed images will be completely uncorrelated. For each hologram, the digitally reconstructed image is stored. Images from many hologram are added and the various noise sources are significantly reduced. For example, if successive exposures are 100 ms. apart, then over a period of 5 minutes, 3000 holograms are formed and their images added, giving a signal to noise ratio improvement of 55. Object instability, which is usually an enemy of holography, now becomes an ally.

Even if the scattering medium is inherently stable, so that exposure times can be long, there is still the problem of speckle noise, which will not be helped at all by longer exposure. It can be eliminated by somehow making the object less stable—for example, by vibrating it. We require, as before, that each exposure be made in a time interval short enough that the medium is stationary, *i.e.*, the speckles don't move, but successive exposure is made at intervals such that the speckle does change. So important is this speckle varying capability that we deliberately cause instability in otherwise stable media. Within a broad range, the more instability the better.

In our experiments, a 6 mm slab of raw chicken meat was placed between two glass plates. An object consisting of two crossed needles was placed behind the chicken. The figure shows (a) the object and (b) the object seen through the meats in ordinary illumination. The object is totally invisible. Part (c) shows the image formed by a single hologram and (d) shows the image after 75 images have been added. The needles (0.5 mm in diameter) are well resolved; we estimate the resolution to be about 0.1 mm.



EXPERIMENTAL RESULTS.

REFERENCES

1. M.A. Duguay and A.T. Mattick, "Ultra-high speed photography of picosecond light pulses and echoes," Appl. Opt. **10**, 1971, 2162-2170; K.M. Yoo and R.R. Alfano, "Time-resolved coherent and incoherent components of forward light scattering in random media," Opt. Lett. **15**, 1990, 320-322.
2. K.G. Spears *et al.*, "Chrono-coherent imaging for medicine," IEEE Trans Biomed. Eng. **36**, 1989, 1210-1214.
3. H. Chen *et al.*, "Two-dimensional imaging through diffusing media using 150 fs gated electronic holography techniques," Opt. Lett. **15**, 1991, 487-489.