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ULTRASONIC HOLOGRAPHY IN OPHTHALMOLOGY — PHYSICAL CONSIDERATIONS *

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The characteristics of the ultrasonic holography unit under clinical trial in ophthalmic applications is discussed with particular emphasis on its advantages and limitations. Discussion of the factors influencing the quality of pictures in B-scanning and holography is also given.

1. Introduction

The ultrasonic A and B-scans have found continued application in ophthalmology since the pioneering work of Oksala and Lehtinen [15, 16] and Baum and Greenwood [4], and although both methods of display have their advocates, the most effective diagnostic tool (as in obstetrics) is a combination of both, Thijssen [18]. The maximum potential of either technique is only achieved by experienced operators, and the temptation to collect and store information from three dimensions for subsequent retrieval and assessment by clinicians has proved irresistible.

Computing techniques, involving the collection and storage of serial A-scans or B-scans (e.g. Milan [14]) are severely limited in ophthalmic applications because of the very high sampling rates required at the high frequencies (typically 8-15 MHz) used in diagnostic ophthalmic ultrasound, and also because of the great volume of data that has to be stored and processed. Compared to these difficulties, the analogue approach of holography appears at first sight to be favoured in application to the eye, which is accessible, has low attenuation coefficients (typically 0.1 dB/cm for the ocular media) and a regular anatomy in the normal. The bony protective socket in which the eye sits demands a reflection technique, since the transmission methods of holography favoured by investigators for other areas of the body (Holbrooke et al. [11] and Metherell [13]) are rendered impotent by the variability in the attenuation of skull bone (Curry et al. [8]).

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As with all current forms of acoustical holography, the greatest problem is presented by the lack of a suitable acousto-optical converter or a means of recording the ultrasonic intensity distribution over an area of linear dimension much larger than the wavelength with a resolution of the order of a wavelength. The liquid surface levitation approach, while permitting real-time visualization is difficult to implement in a clinical situation for ophthalmic investigations. Apart from the multiplexing of B-scans (GREGUSS [9]), two solutions have been suggested to date.

The first of these (GREGUSS and BERTENYI [10]) used the interrogating beam from the transducer as the reference beam. The beam irradiating the eye passed through a sonosensitive plane that intercepted the reflected echoes, and, after development, provided the hologram. It would appear that the poor resolution and lack of easily-interpretable reconstructions has prevented continued use of this technique.

ALDRIDGE et al. [1] described in 1971 a pilot study with a system employing a mechanically-scanned transducer to sample over an aperture above an excised eye. Multiplication of the time-gated echoes from a region of the eye with an electronic reference related to the tone-burst exciting the transducer permitted the hologram to be constructed point by point on a facsimile recorder. Modification of the technique was required (ALDRIDGE et al. [2]) before it could be evaluated clinically. The philosophy of the prototype built for clinical use has been discussed fully elsewhere (ALDRIDGE et al. [2]). This paper discusses the demands of the clinical environment upon the development of the machine, indicates some of the difficulties associated with its use as a clinical tool and concludes with a discussion of the studies that will be necessary for its meaningful evaluation.

2. Machine-patient interface

The scanning mechanism built at the Atomic Energy Research Authority, Harwell provided a rectilinear scanning mode for the transducer over an area 4 cm square. The 10 MHz transducers used were sharply focussed at a distance of about 1 cm from the crystal face and the focal plane (because of instrumental requirements) needed to be about 2 cm above the eye being investigated (Fig. 1). In order to couple the transducer to the eye, some form of water bath was required. The open bath was used, consisting of a surgical drape filled with hyponormal Ringer's solution at 37 °C and supported by a square metal frame (Fig. 2). The assembly of the bath takes a skilled operator 5-10 minutes, but has the advantages over the closed type of bath (which is applied to the closed eyelid) of removing the acoustical complication of the membrane and coupling grease at the bottom of the closed bath, and allowing the eyelid to be open to obtain better penetration. The use of a single eye bath precludes the easy comparison of scans from one eye with those from the other, but in cases where the free eye is sighted, it may be employed to keep the direction of gaze fixed (with a fixation light). The frame supporting the surgical drape is attached to a bar at the side of the bed, to enable it to be adjusted to the correct position over the patient's eye. The scanning area of the transducer is located with the aperture of the frame by suspending the transducer scanning movement from a gantry (Fig. 3), along which it may be moved. Adiustment is completed by movement of the patient's bed in a direction perpendicular to the gantry and

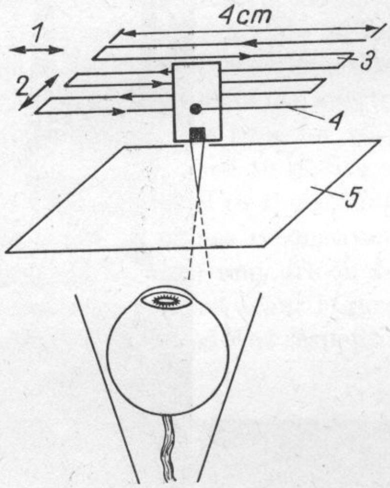


Fig. 1. Scanning geometry

1 – fast scanning, *2* – slow scanning, *3* – surface of scanning, *4* – transducer, *5* – focal surface

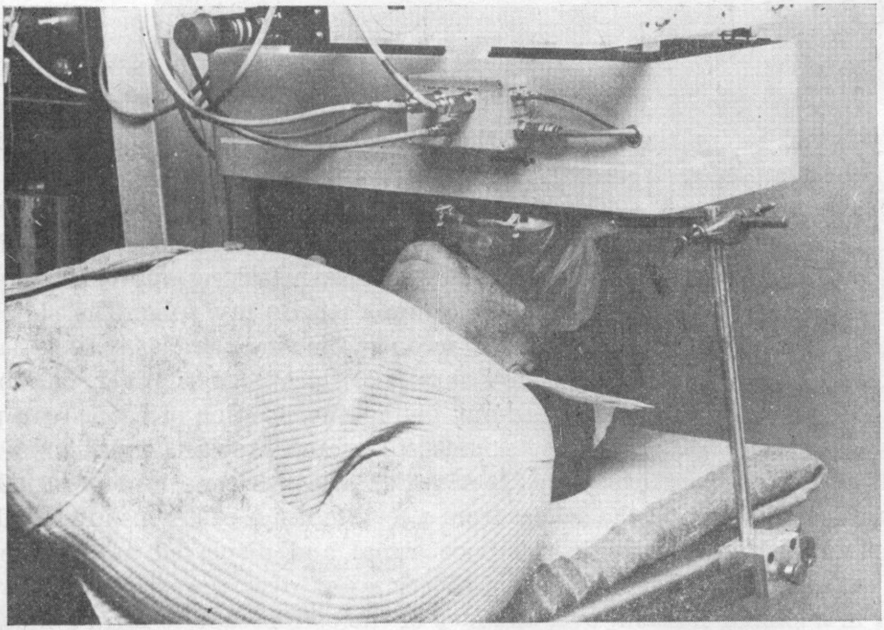


Fig. 2. Scanning mechanism and water bath on eye

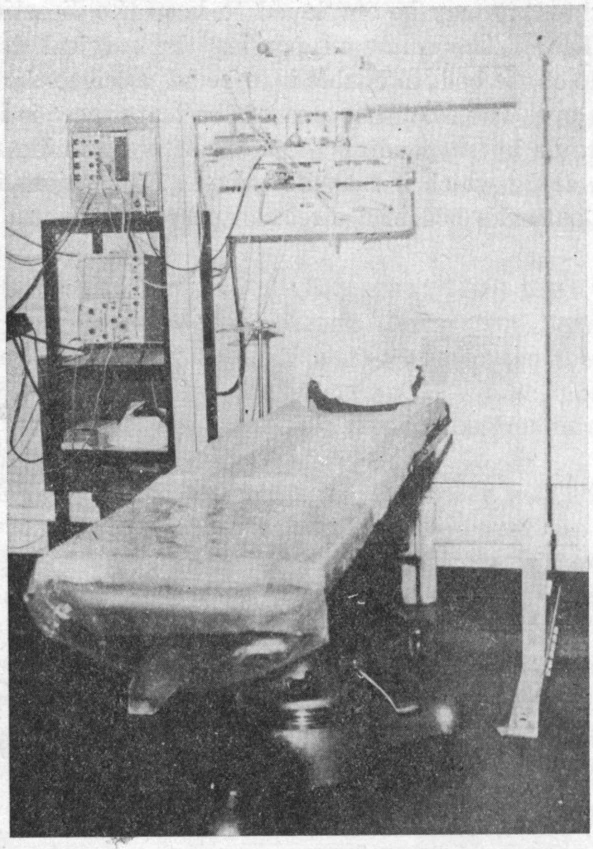


Fig. 3. Gantry and scanning mechanism

finally by adjusting the height of the bed (using a hydraulic pump) until the tip of the transducer is just in the water bath.

The scanning regime (described by ALDRIDGE et. al. [2]) consists of a fast linear scan in one dimension coupled with a slower scan in a perpendicular direction. With each 4 cm sweep of the fast scan (taking approximately 120 ms) a B-scan is produced on a non-storage cathode ray tube. The slow scan of 4 cm may take between 12 and 23 seconds allowing the fast scan to sample between 1/2 mm (80 lines) and 1/4 mm (160 lines). Alternatively it may be adjusted manually, a digital read-out giving the position of the B-scan plane displayed relative to an arbitrary origin with an accuracy of 1 mm.

The transducer is excited with a variable length tone burst of 10 MHz. To produce a hologram, the echoes from a certain range of depths are gated out, multiplied with an electronic reference signal and displayed as an intensity on a cathode ray tube. As the transducer scans over the aperture, the spot scans, in a similar fashion, over the face of the oscilloscope to form a hologram by being integrated onto a «Polaroid» negative film. Development of the film takes only 3 minutes after which it may be reconstructed (prior to dismissal of the patient) on an optical bench in a darkroom adjacent to the examination room. The reconstruction may be viewed by eye, or displayed on a closed circuit television system, or recorded photographically.

3. Comparison of B-scanning and holography

The essence of the hologram produced, since it is not reconstructed in real time, is that it provides an easy and compact (it is essentially a slide 35 mm) method of storing ultrasonic information from a three-dimensional volume of soft tissue. The volume of tissue is defined by the limits of the aperture scanned, the delay before the acceptance time gate opens, the time for which the gate is open and the length of the pulse of ultrasound used to obtain the hologram. It is only possible to display a single plane (parallel to the scanning plane) from this volume at any one time. However the planes reconstructed are inaccessible to any B-scan (because of the orbital wall) and are in fact perpendicular to those of the B-scans displayed from the fast-scan. Figure 4 shows the B-scan of an excised eye (the long pulse length used was responsible

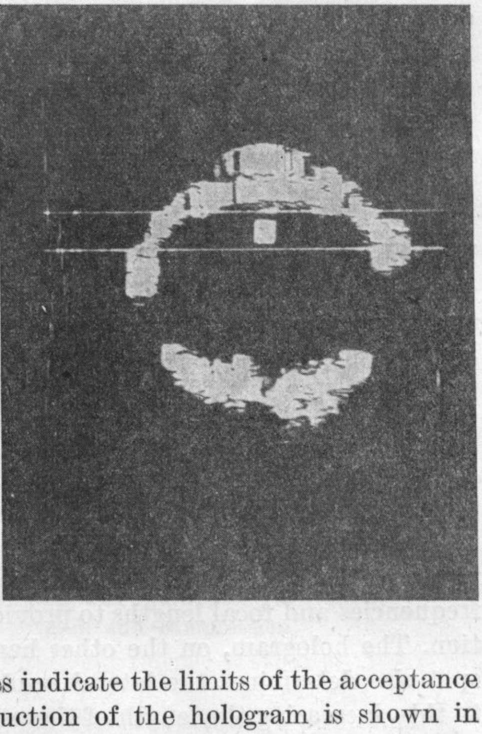


Fig. 4. B-scan of excised eye. The poor resolution is caused by the use of a long pulse length

for the poor resolution). The two white lines indicate the limits of the acceptance gate for making a hologram. A reconstruction of the hologram is shown in Fig. 5, where the circular nature of the cross-section of the eye can be clearly

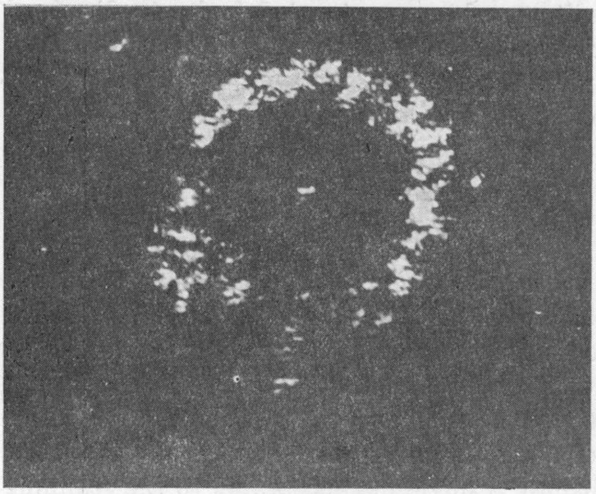


Fig. 5. Reconstruction of hologram taken of the volume between the horizontal lines representing the acceptance gate on Fig. 4

seen, as can the back of the lens (appearing as a bright spot in the centre). The ragged nature of the outer ring is due to attached tissue.

ALDRIDGE et al. [2] using targets with simple geometry have shown the lateral resolution of the hologram to be of the order of 0.5 mm and the depth resolution to be approximately 5 mm. The depth resolution of the B-scan depends entirely on the pulse length which may be varied down to 0.5 μs ($\simeq$ 0.3 mm of tissue for a pulse-echo system); while the lateral resolution depends on the focussing properties of the transducer. Consideration of the means of optimizing the two different displays shows that they present conflicting requirements, as summarized in Table 1 (CHIVERS [7]). The B-scan requires

Table 1. Parameters for optimizing displays

	Pulse length	Transducer	
		focal length	focus
B-scan	Short for good resolution	Medium (chosen for region of interest)	Weak
Holography	Long for good signal to noise ratio	Short	Sharp for good resolution

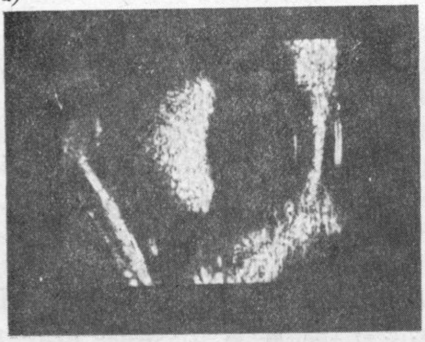
a weakly focussed transducer that has its minimum beam width in the region of diagnostic interest, and should be excited by a very short pulse. Ideally a range of transducers should be available (BUSCHMANN [6]) with different frequencies and focal lengths to provide the optimum display for a clinical condition. The hologram, on the other hand, requires a very sharp focus (the focal spot size determines the lateral resolution) close to the transducer. In addition to this, increasing the length of the pulse used to excite the transducer generally increases the signal to noise ratio of the hologram.

4. B-scanning

The value of a linear B-scan is limited severely in ophthalmic applications by the adverse geometry of the anatomy of the eye, with the convex refracting surfaces it presents to the interrogating sound beam (SOKOLLU [17]). The limitations are even more severe if unfavourably focussed transducers are used. Nevertheless, the B-scan incorporated into the holographic system has several uses. Its main use is to provide a visual monitor of the position of the hologram gate, permitting its quick and confident adjustment (see Fig. 4).

As a diagnostic tool in its own right it has the usual (and necessary) variable gain and swept gain. In addition to these, the display includes a compression amplifier to display «grey-scale» pictures of the orbital fat, and a variable pulse length. The diagnostic trials in progress are aimed at determining the optimum use of these four mutually dependent parameters that effect the display. Figure 6 shows the effects of a) high gain and low swept gain, b) low gain and high swept gain, and c) low gain and low swept gain with compression for a particular (short) pulse length.

a)



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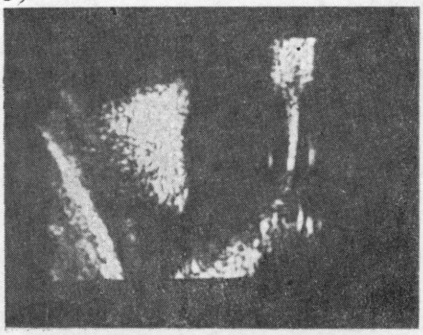

c)

Fig. 6. Effect of a) high gain and low swept gain, b) low gain and high swept gain, and c) low gain, low swept gain and compression

The clinical value of the B-scan has yet to be assessed, although preliminary results with detached retinas, ocular and orbital tumours and intra-ocular foreign bodies are encouraging. The fast nature of the scan makes it an almost real-time display that can be used with advantage in dynamic studies. Figure 7 illustrates the value of the scan in the localization of a foreign body. The scanning mechanism has been rotated through 90° to permit the fast scan to run from head to toe of the patient. Manual adjustment of the slow scan enables the echoes from the cornea and front of the lens to be maximized (lower picture). The reading on the slow-scan position scale is taken as the reference to be subtracted from the reading at the position corresponding to the maximum

a)

b)

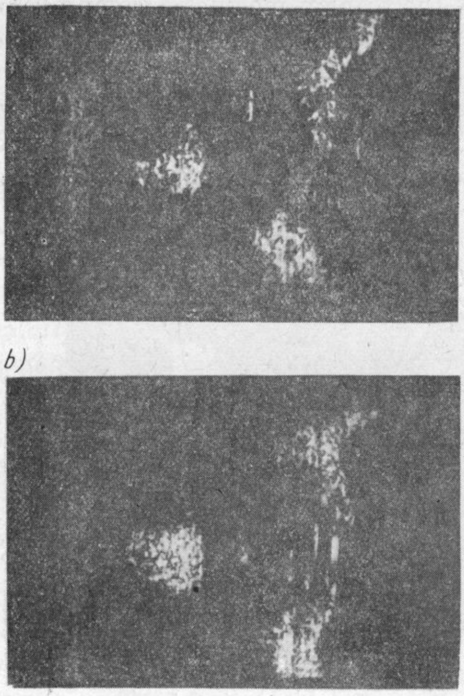

Fig. 7. a) Foreign body echo in upper globe maximized, b) 7 mm lateral to (a) the corneal and anterior lens echoes are maximized

echo from the body (seen in the upper picture). Some vitreous disturbance can be seen in the lower picture, while both pictures show clearly the shadowing of the eyelid in the orbital fat patterns. The accuracy of this localization (to < 1 mm) is comparable with that of the methods used in the operating theatre to determine the location of the incision, and has the advantage over the normal radiological examination in that it does not depend on an average globe diameter of 24 mm. However, the position at which the echo is maximized depends on the shape, size and material of the body, and this must be borne in mind during the investigation. In particular, a negative result does not exclude the existence of a foreign body (an unfavourably orientated air-gun pellet, for example, reflects almost no echoes to a linearly scanned transducer).

5. Holography

The figures of the resolution specified earlier were obtained using targets of known simple geometry, with a greater acoustic mismatch to their surroundings than is represented by an element of soft tissue in the eye. They therefore represent the optimum rather than the norm that might be expected in a clinical situation. There are two elements in the assessment of clinical holograms: firstly the signal to noise ratio, and secondly the interpretation of the patterns in the reconstruction.

Four factors can contribute noise to the hologram reconstruction:

1. dust or scratches on the hologram itself – these may be minimized with careful handling,

2. movement of the eye during the scan – sometimes the patient's eye follows the movement of the scanning mechanism in the slow-scan direction. This can be minimized with a fixation light for those patients with binocular vision, but blinking or similar muscular contractions may degrade the information content of the hologram,

3. the effect of paths through different tissues (particularly the lens) on the phase of the waves scattered from a certain depth,

4. information from planes in the hologram volume, other than the one that is in focus (and thus being reconstructed).

The maximum signal to noise ratio is thus achieved by using long pulses, using the maximum sampling rate for the fast scan consistent with the transducer focal spot size, and by taking a hologram of only a thin slice.

In the globe, the problem of pattern recognition is relatively simple since the normal is a black circle surrounded by a white ring of tissue, and any signal in the circle suggests a pathological condition. One advantage of the hologram is the visualization of regions close to the lateral walls of the globe, that are relatively hard to investigate with B-scans (although they do not present great problems to the hand-held A-scan).

In the orbit, as with B-scans, the normal hologram is a diffuse echo pattern of apparently random intensity (with perhaps some dark area identifiable as the optic nerve). Regions of foreign tissue may be detected, but their interpretation will need some care as their appearance on the reconstructed hologram will depend upon both the nature of the tissues above them (through which the sound pulse had to travel and return) and the tissues on each side of the reconstructed plane (that are contributing out-of-focus information). In addition to this the holograms can be affected by shadowing and multiple reflection artefacts, although careful attention to the B-scan display may detect these last.

Figures 8, 9 and 10 are reconstructions of holograms taken using stranded targets as a preliminary investigation of the significance of some of these effects. Figures 8 and 9 are reconstructions of a target of parallel nylon lines of 1/8 mm diameter, spaced by 2 mm. Two centimetres above these an acrylic lens implant was supported by three lines of the same nylon thread. In both figures the black image of the lens implant can be seen. It is thought that this is a reflection artefact caused by the strong reflecting characteristic of the plastic compared to that of its supporting nylon strands which cannot be detected in the image

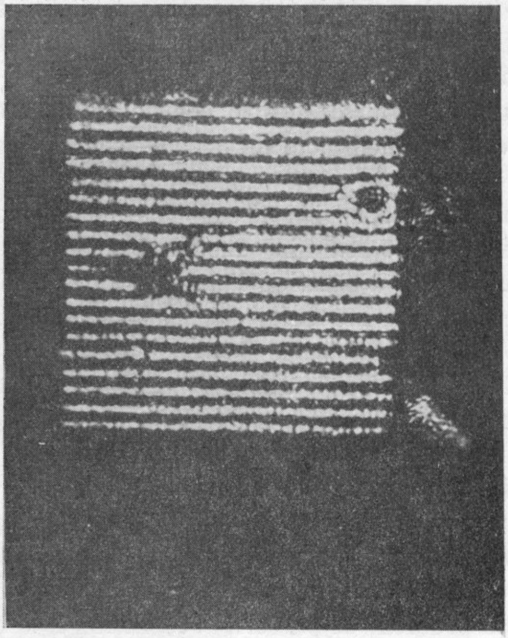

Fig. 8. Reconstruction of nylon thread target (thickness 1/8 mm, spacing 2 mm) with acrylic lens implant suspended 2 cm above. The black circle is caused by a small air bubble on the line supporting the lens implant

plane. In the top right hand section of Fig. 8 the effect of a small air bubble on the nylon supporting the lens implant can be seen. As expected, this appears as a dark patch with distortion of the pattern of the threads that are being visualized underneath it. This is the effect that might be anticipated from a small bubble of air caught for example in the eyelashes of a patient. Figure 9 shows the same target but with a small air bubble actually on one of its wires. This has less distorting effect than the bubble in Figure 8, but produces an (expected) strong highlight.

Figure 10 is the reconstruction of a freshly excised human anterior chamber with some attached tissue suspended 2 cm above a grid of parallel copper wires of 1/8 mm diameter spaced by 1.5 mm and is very much more disturbing. The extremity of the tissue appears to be matched by a thin dark line on the right-hand side of the picture. Immediately to the left of the line the pattern appears to be only minimally distorted, but it appears that in the centre or

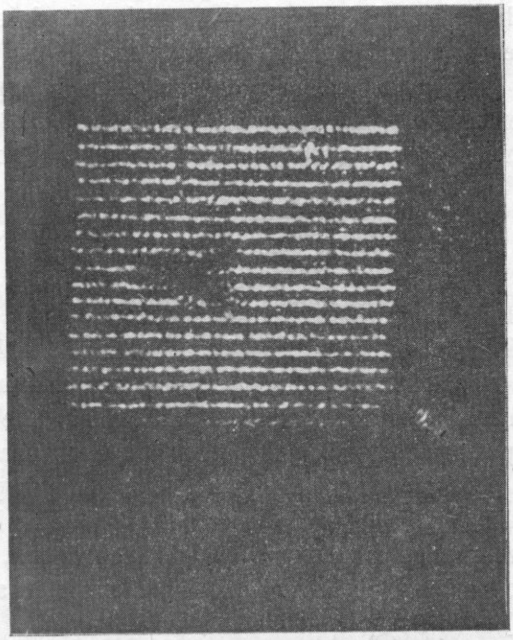

Fig. 9. As Fig. 7, but with air bubble actually on one of the threads being visualized (second from top)

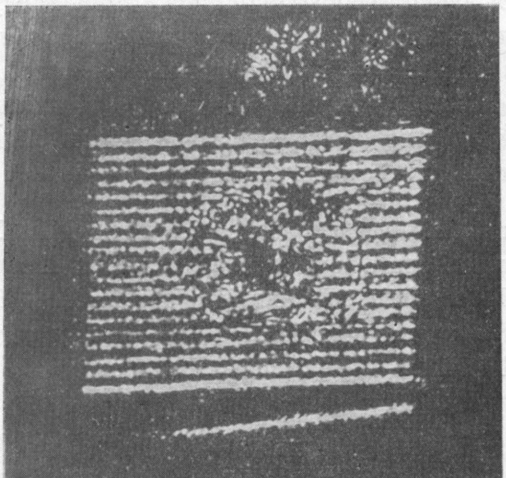

Fig. 10. Reconstruction of copper wire target (thickness 1/8 mm, spacing 1.5 mm) with freshly excised anterior chamber supported 2 cm above

where there is any thickness of tissue the pattern is completely lost. The darkest patch in the centre may represent a shadow caused by a relatively strong reflection from the lens, but the effect of the surrounding tissue is salutary. The relation between this picture and that reported by BOLDREY et al. [5] is not yet clear. The brightening effect of the lens that they report may be a diffraction phenomenon.

6. Conclusion

The characteristics of the ultrasonic holography unit under clinical trial at Moorfields Eye Hospital, London have been discussed with particular emphasis on the physical limitations of the linear B-scan and holographic displays it provides. The clinical trials in progress are aimed, for the B-scan, at defining the relative roles of gain, swept gain, pulse length and compression characteristics for different clinical conditions; and for the holographic display of assessing its potential and limitations as a new diagnostic method. The latter require assessment not only in relation to existing ultrasonic techniques, but also in relation to other methods of orbital examination. This work is already in progress (AMBROSE et al. [3]).

In addition to this, further laboratory studies are needed to assist in the interpretation of the diffuse orbital fat echo patterns and the effect of the overlying tissue upon them. The degradation of the signal to noise ratio by planes in the hologram not being reconstructed may limit the practical use of the system to the visualization of thin slices rather than substantial volumes. The relative merits of the holographic system compared to a simple C-scan (e.g. McCREADY and HILL [12]) will then need evaluation.

The answers to these questions will evolve from the clinical trials in progress which will be reported subsequently.

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