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X-Ray Image Intensifiers: Design and Future Possibilities

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X-ray image intensifiers: design and future possibilities

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[Plate 1]

The most significant parameters of X-ray image intensifiers are considered in relation to their main components, the X-ray detection screen, the photocathode, the electron optics and the output screen. It is shown how these parameters define the limitations to the performance of an intensifier in terms of resolution, contrast and noise.

The prospects for further improvements in the performance of X-ray image intensifiers are outlined, by modifications of the conventional design, and also by alternative technical approaches.

Introduction

X-ray image converter tubes were designed to assist medical diagnosis. The guiding principle in their design has therefore been to minimize the X-ray dose. Although the use of these tubes has subsequently been extended to applications outside the medical field, where the same restrictions may not apply, no one of these applications has so far warranted the development of special tubes, optimized for that particular use.

The dose restriction in X-ray imaging leads to a scarcity of available X-ray quanta, aggravated by their high energy and resulting in two important general requirements. The first is to detect the largest possible fraction of the incoming quanta and ensure that each detected quantum can give rise to a 'registration' on the retina of an observer's eye. The second requirement follows from the fact that the statistical fluctuations in the numbers of X-ray quanta detected at the input set a limit to the smallest picture detail just discernible. Any degradation in picture contrast by individual components of an X-ray image converter will further reduce perceptibility, and should therefore be minimized.

The need for X-ray image intensification

The first requirement explains the need for image intensification. One absorbed X-ray quantum can cause a scintillation, comprising a few thousand visible photons, in a phosphor screen. In fluoroscopy, when an observer looks directly at such a converted picture, at least 10^5 photons must be produced on the screen to ensure the registration of one photon on the retina of a fully dark adapted eye. Most individual scintillations therefore fail to register, leading to a considerable loss of information. For single-shot exposures in full-size fluorography, this loss can be avoided by placing the screen in contact with a photographic plate, but this makes it impossible to observe movement. Another way of ensuring that no individual scintillations are lost, while retaining the ability to observe movement, is to increase the number of photons per scintillation by image intensification (Coltman 1948; Teves & Tol 1952).

THE X-RAY IMAGE INTENSIFIER TUBE

The principle of operation is indicated in figure 1. An X-ray quantum, absorbed in the fluorescent input screen, produces several thousand visible photons. These photons are converted into photoelectrons by a photoemissive layer, usually consisting of a thin coating (a few tens of nanometres) of one or more alkali antimonides, deposited on the vacuum side of the input phosphor screen and emitting one photoelectron for every five to ten incident photons.

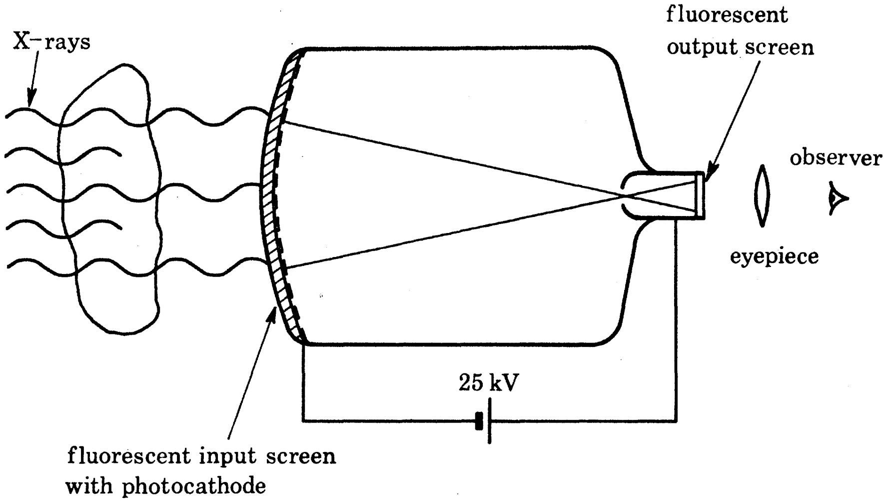

FIGURE 1. Principle of operation of an X-ray image intensifier tube.

The photoelectrons are accelerated and focused to form a diminished image on the output screen, where more than a thousand visible photons are produced per incident photoelectron. The gain exceeds 100 times, which brings the total number of visible photons produced on the output screen per detected X-ray quantum well above the minimum, 10^5, required for direct viewing.

In addition, the diminution $(1/m)$ of the image intensifier tubes allows the use of an eyepiece with magnification m at the viewing end, which raises the collection efficiency of the pupil of the observer's eye by a factor m^2. It also raises the brightness of the viewing screen by a further factor m^2, making it unnecessary for the observer to be dark-adapted.

Figure 2 shows the comparison between a direct-viewing fluorescent screen and an X-ray image intensifier tube, in relation to the numbers of information carriers for an object of about 0.1 mm^2, at the various stages between X-ray source and retina. For a direct-viewing screen it illustrates the loss of carriers due to inadequate photon gain. The image intensifier tube, however, is limited only by the quantum detection efficiency of the fluorescent input screen, i.e. the fraction of the incident X-ray quanta which cause a scintillation.

THE FLUORESCENT INPUT SCREEN

The other important variable of the fluorescent input screen is its modulation transfer function (m.t.f.). This function expresses the degradation in contrast caused by any component of an imaging instrument. The m.t.f. of a complete instrument, consisting of a number of different optically linear components, can be found by multiplying the individual m.t.f. curves.

Optimization of both quantum detection efficiency and modulation transfer in the fluorescent input screen can lead to conflicting requirements. The detection efficiency depends on the thickness of the phosphor layer which is needed to absorb the maximum fraction of the incident X-ray quanta. With the older types of screen, consisting for example of sedimented phosphor grains of $ZnCdS_2$:Ag, increased thickness causes more scatter of the visible light produced, thus decreasing the modulation depth in the finer patterns. For this reason modern X-ray image converter tubes contain detection screens, for which special efforts have been made to reduce scatter (Bates 1969), e.g. by using a layer of evaporated CsI:Na. The main advantages of such a screen result from the combination of high packing density, the high atomic absorption of CsI for diagnostically significant X-ray energies, and the anisotropic light propagation in the evaporated film (Stevels & Schrama-de Pauw 1974).

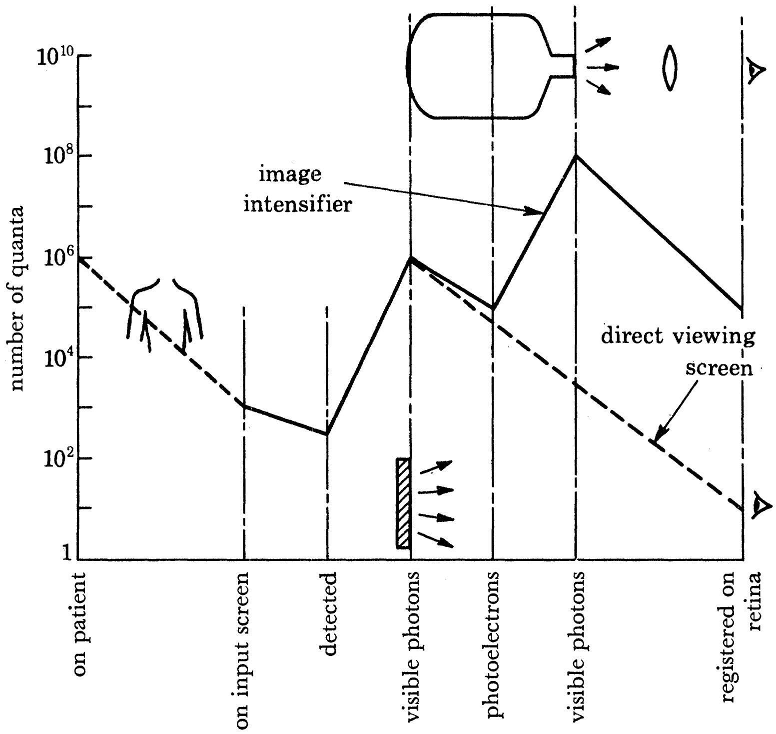

FIGURE 2. Information carrier densities in an X-ray image intensifier tube in comparison with a direct-viewing fluorescent screen.

THE ELECTRON OPTICS

The substantial electron optical diminution in the tube has two further advantages. It minimizes the length and therefore the mass of the tube, and a smaller output image is more compatible with the input diameter of further components, such as television camera tubes and cine film. For this purpose electrostatic systems, based on the focusing properties of concentric spherical electrodes (Schagen *et al.* 1952), illustrated in figure 3, are particularly suitable. In practical tubes there is a restriction on the tube diameter, which should exceed that of the input screen as little as possible, while the input screen–photocathode sandwich should be as flat as possible to avoid excessive X-ray picture distortion.

The concentric sphere approach can be modified to minimize the effects of the electron optical aberrations. Apart from 'chromatic' aberration, which is always present and is caused by the differences in angle and energy of the emitted photoelectrons, the departure from the ideal concentric sphere introduces geometrical aberrations, such as astigmatism, coma and image distortion.

In most cases the optimum design requires the addition of at least one extra electrode and, for some applications, the introduction of one or two further electrodes adds the useful possibility of varying the diminution. This is used in some modern tubes to enable switching between two or three different sizes of input image field.

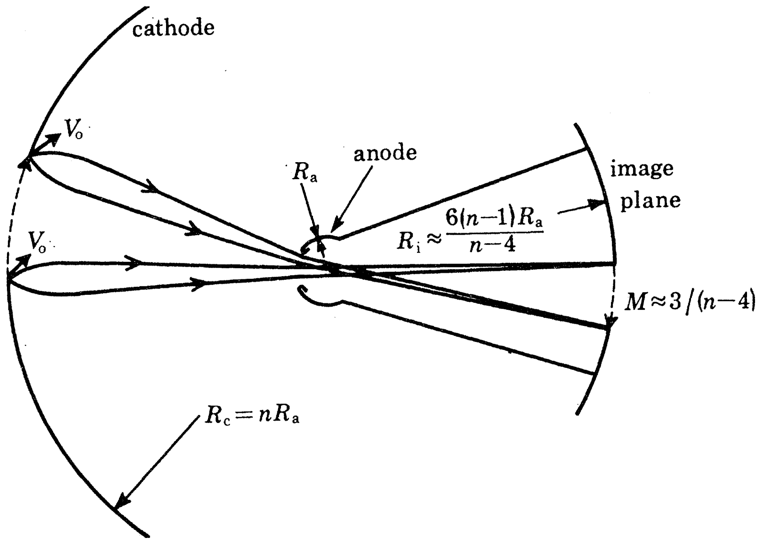

FIGURE 3. Schematic diagram of electron optical imaging properties of concentric spherical electrodes.

The output screen

The output screen, converting the photoelectrons back into visible photons, consists of a thin layer (*ca.* 5 μm) of small phosphor grains (*ca.* 1 μm). The screen is covered on the vacuum side with a thin (*ca.* 0.1 μm) evaporated aluminium film, which is virtually transparent to the photoelectrons but reflects the visible light produced in the phosphor.

The m.t.f. of such a screen extends to spatial frequencies of more than 2000 line pairs cm^{-1}, but this is reduced by the electron optical diminution in the tube to a correspondingly smaller equivalent value when referred to the image on the input screen.

If the phosphor is deposited directly on a clear glass output window, multiple reflexions inside this window can cause degradation of the m.t.f. due to halation. This effect can be avoided by the use of a fibre optic output window, with the additional advantage that the inside can be curved to correct for image curvature and distortion, and which facilitates optical coupling to a television camera tube.

The performance of an X-ray image intensifier

Performance can be described with the aid of 'acuity curves' relating the minimum size of picture detail, which can just be detected in the output image, to the intensity of the incident X-ray radiation and the contrast at the input.

The calculation of these curves is similar to the derivation of acuity curves for other imaging instruments (Schagen 1971), leading to the expression

$$I_i \tau d^2_{min} = \frac{(S/N)^2_{min}}{2\theta M^2 C_i^2} \qquad (1)$$

where I_i is the average incident X-ray quantum density on two adjacent picture elements forming the picture detail, ($I_i = \frac{1}{2}(I_{high}+I_{low})$), τ is the integration time of the instrument, d_{min} is the minimum size of picture detail just detectable, $(S/N)_{min}$ is the minimum signal:noise ratio required to detect the picture detail (this depends on the degree of certainty required in the detection decision and on the kind of picture detail; for example $(S/N)_{min} = 1$ for a black and white bar pattern), θ is the quantum detection efficiency of the instrument for the type of X-ray quanta received, M is the modulation transfer of the instrument at the picture detail size d_{min}, and C_i is the input contrast in the picture detail, defined in the normal optical way as $C_i = (I_{high} - I_{low})/(I_{high} + I_{low})$.

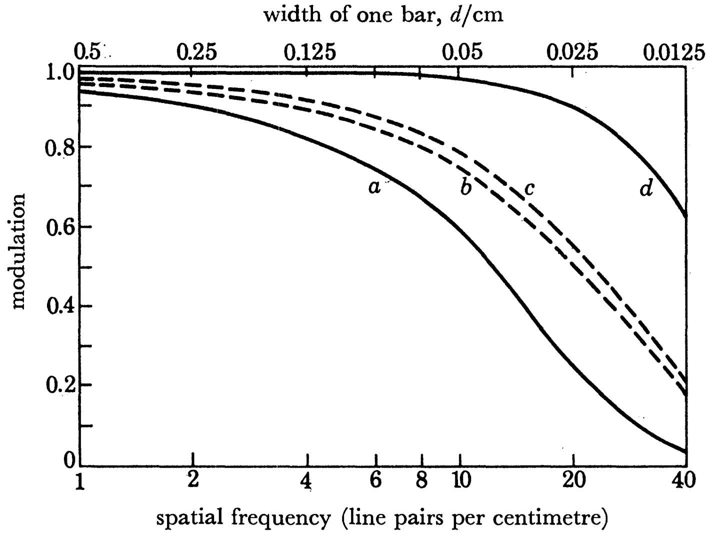

FIGURE 4. Modulation transfer function of the Philips XG2002 X-ray image intensifier tube. (*a*) Complete tube; (*b*) input screen; (*c*) output screen; (*d*) electron optics.

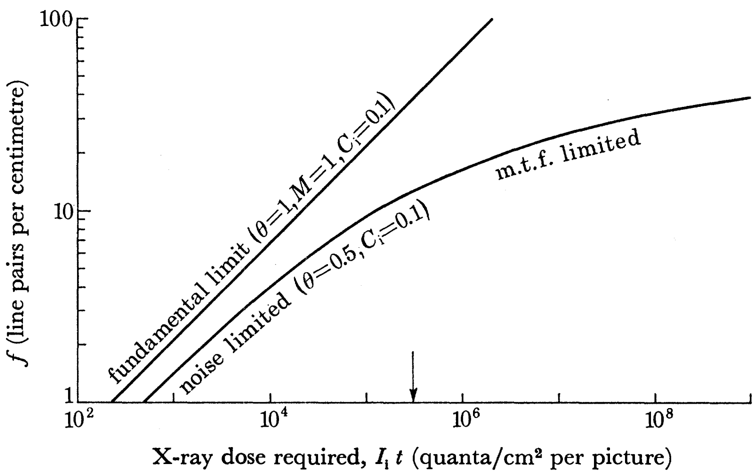

FIGURE 5. Calculated acuity curve of a typical X-ray image intensifier tube: f, the spatial frequency just resolvable, equals $\frac{1}{2}d^{-1}_{min}$. The arrow indicates the typical dose per picture for fluoroscopy, *ca.* 10 μR.

As an example, figure 4 shows the m.t.f. of a typical modern X-ray image intensifier tube (the Philips 15 cm XG2002), together with the m.t.fs of its individual components (Kühl 1973).

In figure 5 a calculated acuity curve of this tube, according to equation (1), is plotted. This shows the smallest size of picture detail still discernible at a given X-ray dose per picture ($I_i \tau$), for black and white bar patterns ($(S/N)_{\min} = 1$) and an input contrast $C_i = 0.1$, in comparison with the straight line of an 'ideal' instrument ($\theta = 1$, $M = 1$). The latter represents the performance limit set by the statistical fluctuations in the numbers of incoming X-ray quanta.

Figure 5 shows how, for the larger picture details, the tube performance is limited only by the noise in the detected X-ray quanta, and how for the smaller details the m.t.f. limitation takes over.

Applicational aspects

An image intensifier tube performance characterized by an acuity curve similar to that shown in figure 5 can be very useful in direct-viewing fluoroscopy. By coupling the tube fibre-optically to a television camera tube, it can be even more usefully applied to television fluoroscopy. The important additional facilities thus provided are registration on cine film or video cassettes, remote viewing and the possibility of processing the video signal. This can include black level and contrast manipulation, noise reduction and edge enhancement.

The good performance of modern image intensifier tubes also permits high quality single-shot spot-film fluorography with reduced picture size (70 mm), which alleviates the storage and supply problems of full-sized radiography.

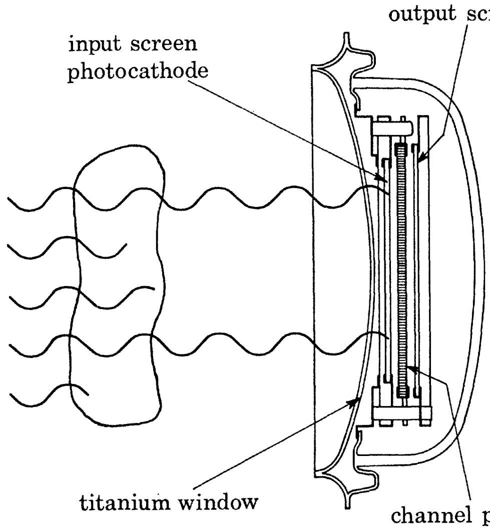

Figure 6. Diagram of an experimental 'channel' X-ray image intensifier tube.

Future possibilities

The scope for further improvements in the conventional type of X-ray image intensifier tube is restricted. Only marginal further increases are possible in m.t.f. and quantum detection efficiency. On the other hand, a flat input screen remains a desirable feature. This would minimize image distortion and ease extraction of three-dimensional information in tomography. In principle this aim can be realized with a 'channel' X-ray image intensifier tube, of which a laboratory prototype was described by Millar *et al.* (1971).

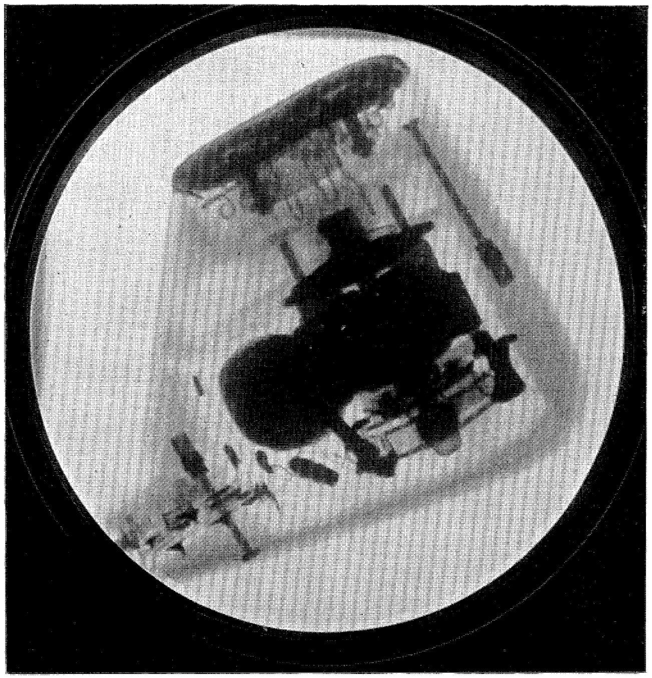

FIGURE 7. Photograph of an image on the output screen of a channel X-ray image intensifier tube.

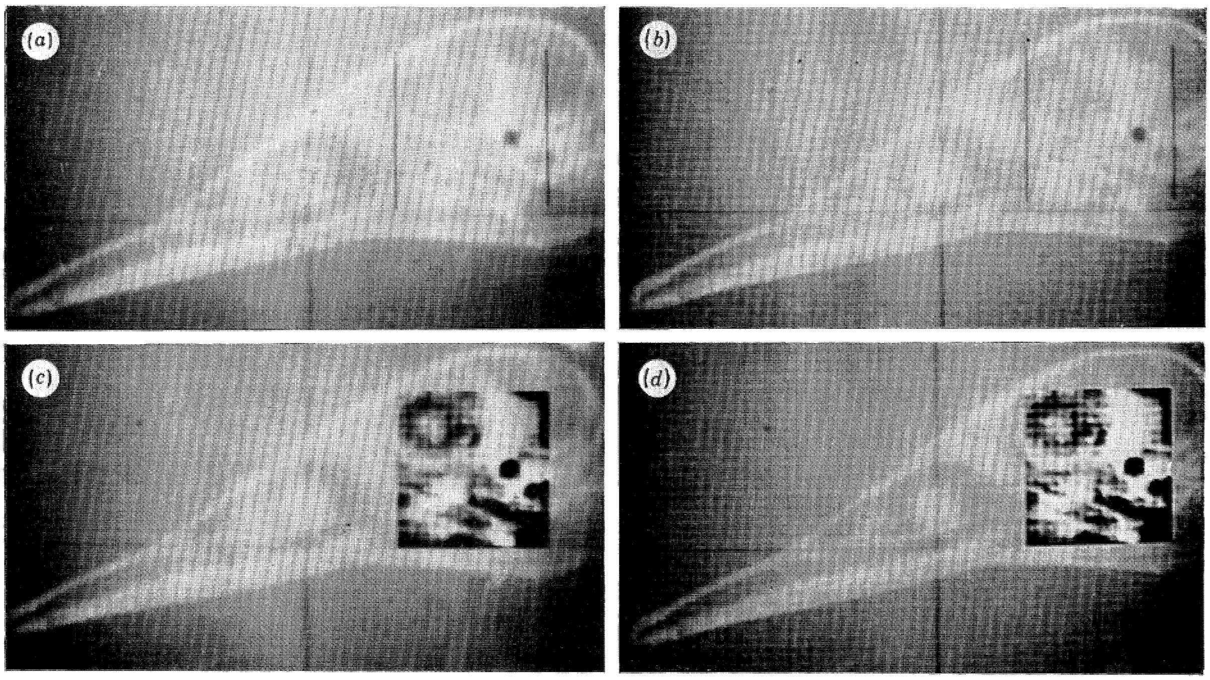

FIGURE 9. Real-time image processing, applied to X-ray image intensifier television pictures. (*a*) Part of an original X-ray image intensifier television picture; (*b*) as (*a*) with edge enhancement applied; (*c*) as (*a*) with contrast equalization applied in a small area; (*d*) as (*b*) with contrast equalization applied in a small area. (Courtesy of L. H. Guildford, Philips Research Laboratories, Redhill, U.K.)

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Such a tube, illustrated in figure 6, consists basically of a flat fluorescent input screen–photocathode sandwich, separated from the parallel fluorescent output screen by a channel plate consisting of a mosaic of very small channel electron multipliers. Electrons move down individual channels, guided by the accelerating electric field, and are multiplied by secondary emission whenever they collide with the wall. Each primary photoelectron entering a channel causes several thousand secondary electrons to emerge from that channel and to be drawn across to the fluorescent output screen. This provides the tube with an overall quantum gain of about 10^7, unity magnification, complete freedom from picture distortion, and an m.t.f. very close to that of the input screen. Figure 7, plate 1, shows the picture on the output screen of such a tube (diameter 15 cm).

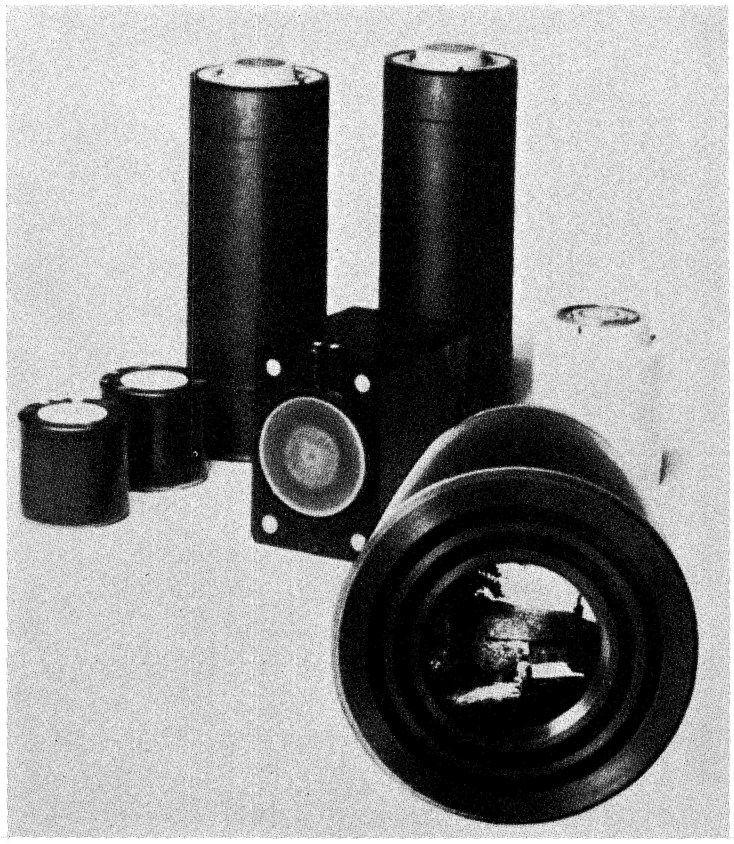

FIGURE 8. Photograph of some 'packaged' image intensifier tubes.

It has not been established whether such a tube could be manufactured with a sufficiently high picture quality, taking into account possible non-uniformities in gain across the area of the channel plate. Owing to its high quantum gain, a tube of this kind could be coupled to a television chain using only a low-aperture lens. Such a system could have a better overall m.t.f. than one using a conventional tube with fibre optic coupling.

A simpler and cheaper alternative to this approach might be provided by the use of a solid-state sandwich panel. Panels consisting of layers of photoconductive and electroluminescent material were first made several years ago (Diemer *et al.* 1955). They were discarded for X-ray conversion because of their slow response to changes in the incoming radiation. It is, however,

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conceivable that further developments in photoconductive materials technology will reduce the prohibitively long decay times of appropriate photoconductors at diagnostically significant X-ray dose rates.

For special applications requiring a much small input field, attractive alternative approaches are now possible (Kühl & Schrijvers 1977). These employ thin fibre optic faceplates, on which the fluorescent input phosphor has been deposited, and which can be optimized for the particular application. Such a detection screen can be coupled directly to the fibre optic window of an ordinary image intensifier, of which different kinds are now available complete with wrap-around power supplies. Figure 8 shows some packaged tubes of this kind, with different sizes of output window, as manufactured by Mullard. The intensified image can be viewed directly on the fibre optic output window, or alternatively can be coupled to the fibre optic input window of a camera tube, thus providing a flexible and compact television fluoroscopy chain.

Finally, a few words about image processing. Stimulated by the American space programme, methods have been developed for improving the quality of pictures received from satellites. The picture is divided into the required number of picture elements, each with its own co-ordinates and signal amplitude or grey level. This information is stored in a digital computer, and the amplitude of each picture element can be modified with the aid of specific algorithms, designed at improving the perceptibility of picture details. For example, for single shot pictures the objective might be to improve the contours, which may have been degraded by inadequate modulation transfer, by using an algorithm providing two-dimensional edge enhancement.

Another algorithm may aim at contrast equalization, providing a more even distribution of picture elements over the discernible grey levels in the picture, by manipulating black level and gamma. If the computer has sufficient capacity and speed, similar techniques can be applied to moving pictures.

It is hoped that video signal processing of this kind can also be applied to television fluoroscopy, without the need for a large and prohibitively expensive computer. Further advances in large-scale integration of semiconductor circuitry are still required to reduce the size and cost of the computing facilities. These steps could include the development of specific components, such as cheap high-capacity field stores.

An indication of what may become possible is given in figure 9, plate 1, which shows an X-ray picture before and after edge enhancement in real time, using hard-wired logic circuits. It also shows the effect of contrast equalization on a small area of the picture.

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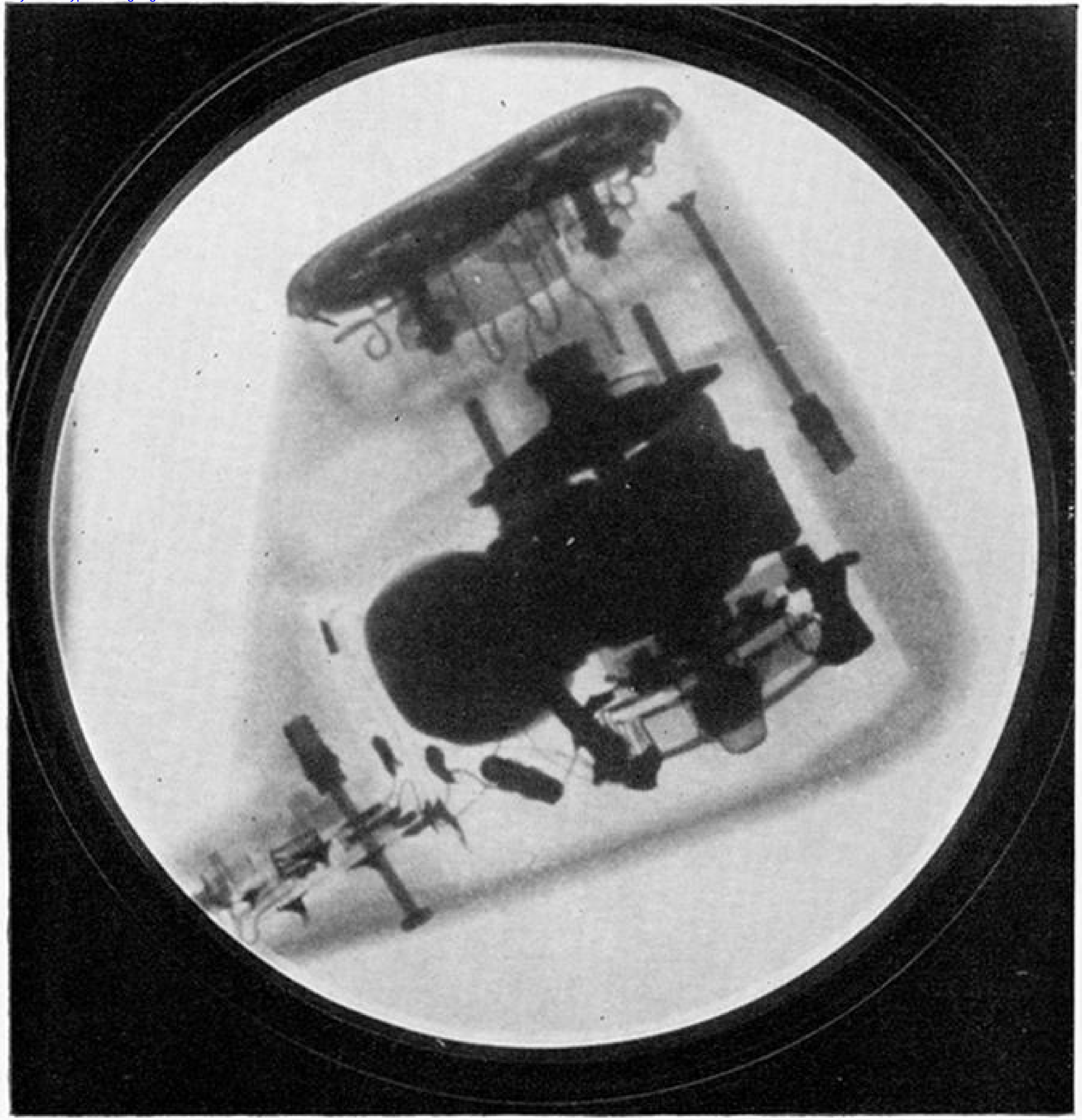

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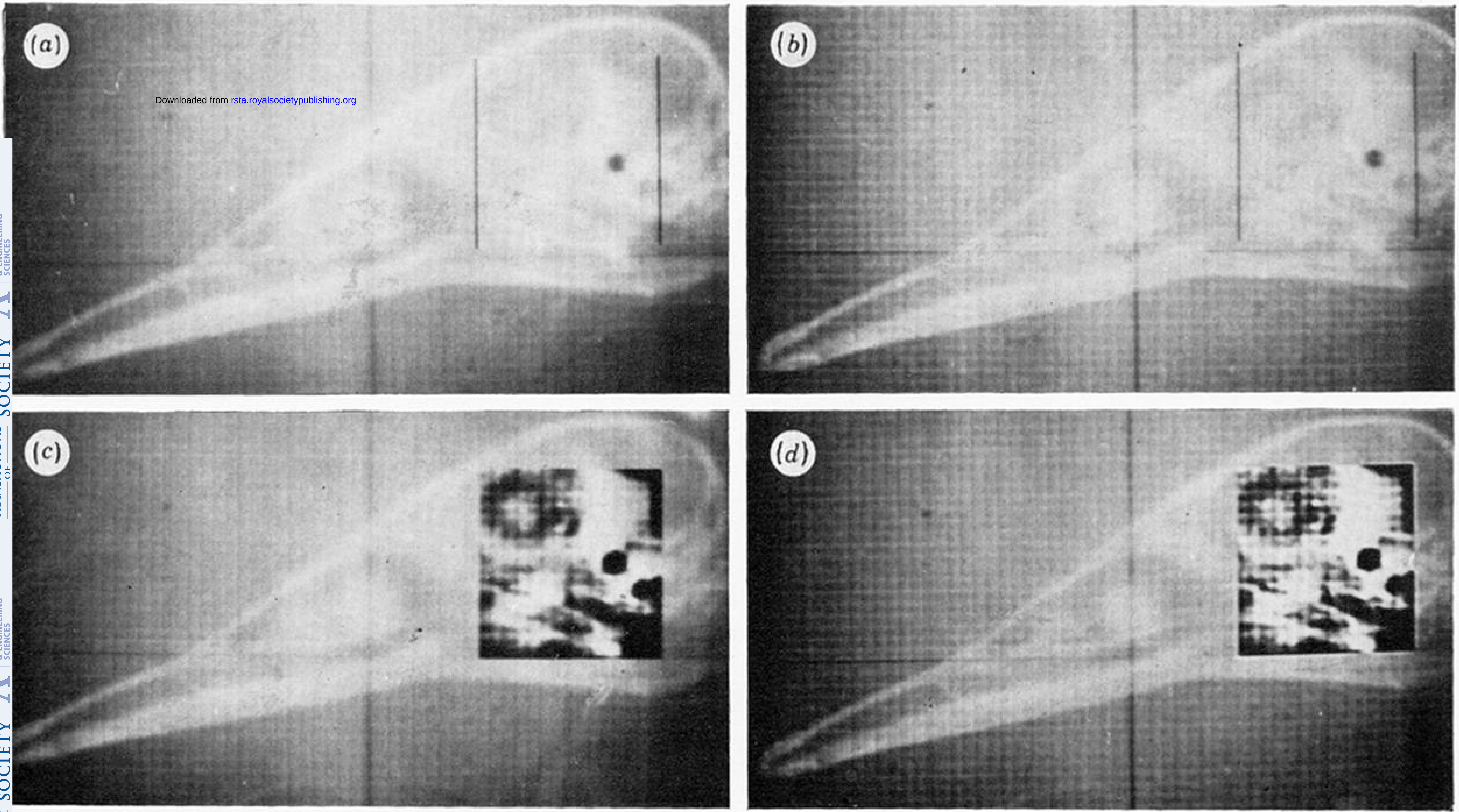

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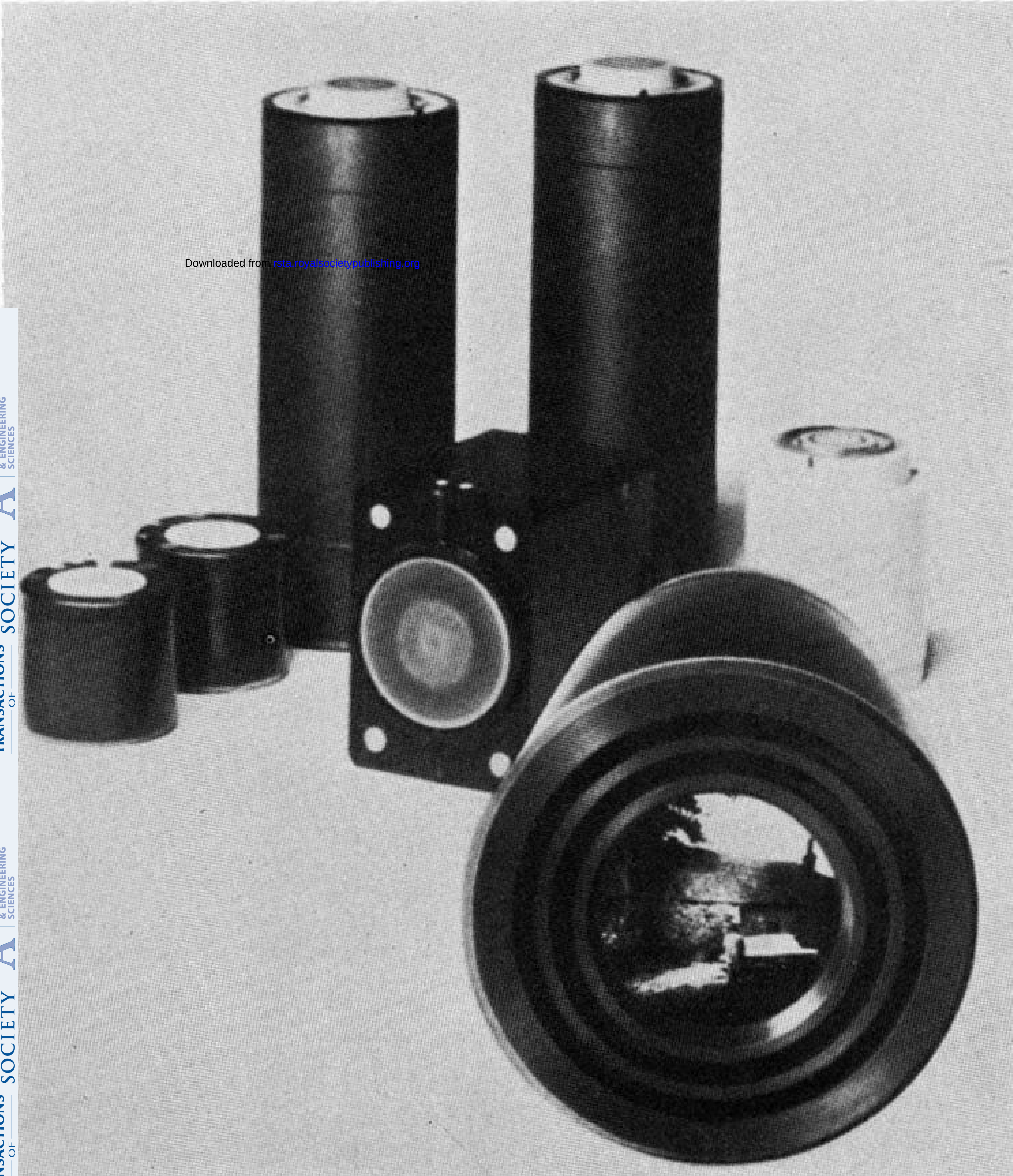

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