In essence, the generation of X-rays, which entails the production of a beam of electrons in a vacuum tube, falls within the technique of electronics. It is a noteworthy point that in X-ray diagnostics the subsequent stage, that is, the conversion to a visible picture of the X-rays which have passed through the object to be examined, is now also tending to become dependent on electronics for a satisfactory solution. In this context it is found that the number of X-ray quanta available virtually sets a limit to the amount of detail in the information that can be derived from fluoroscopy.

The problem of screen brightness in fluoroscopy

X-rays have the capacity to damage or destroy human tissue. In X-ray therapy, use is made of this fact by exposing morbid tissue to these rays for such periods and at such intensities that in total it will receive a certain, heavy, dose. In X-ray diagnostics, on the other hand, care must be taken that patients receive the smallest possible dose during examination so that they will not suffer any injurious consequences, even as a result of repeated examinations.

Using the conventional method of fluoroscopy, therefore, the radiologist must do the best he can with an X-ray image of very low brightness. In fact, for a given duration of an examination (a few minutes at the most), limitation of the total dosage means limitation of the dosage rate to which the patient may be subjected and, accordingly—dependent upon the absorption of the rays by the patient—limitation of the brightness that can be obtained from the screen. In gastric fluoroscopy, for example, with the X-ray tube operating on a voltage of, say, 90 kV and a current of 2 mA, the image obtained on a high-quality screen has an average brightness of about 0.003 cd/m². For comparative purposes it may be said that the average brightness of a landscape by the light of the full moon is 0.01 cd/m².

In order to be able to make a good visual assessment at such low brightness values, the radiologist must first remain in darkness for at least 15 minutes, so that his eyes may be adapted to the low brightness level. Even so, his visual acuity and contrast sensitivity 1) are then fairly low. Hence, for the diagnosis of conditions involving slight abnormalities which often reveal only a low contrast, this is a very inconvenient limitation. It will therefore be easily appreciated that, since the inception of X-ray diagnostics, higher image brightnesses have been an ever-present need.

If more information is to be obtained from the fluoroscopic screen and at the same time a solution found for the problem of the necessity for dark adaptation of the eyes, an increase in image brightness to the extent of at least a factor of 100 to 1000 is needed, as pointed out by Chamberlain in 1942 2). It would not be possible to achieve this simply by increasing the efficacy of existing types of screen; these convert roughly 5% of the X-rays falling on them to visible radiation, and this radiation has approximately the most advantageous wavelength (i.e. in the yellow-green part of the spectrum, where, for a given strength of the radia-

1) Visual acuity is defined as $1/a$, where $a$ is the angle subtended by the finest distinguishable detail. Contrast sensitivity is defined as $1/c$, where $c$ is the lowest distinguishable contrast $A/B$: in this, $B$ is the brightness of the background and $B \pm A$ the brightness of an object seen against that background.

2) W. E. Chamberlain, Fluoroscopes and fluoroscopy, Radiology 38, 383-413, 1942.
theoretically possible in this way would not exceed a factor of 20.

In recent years several methods, using electronic aids, have in fact been devised for intensifying the brightness of the fluoroscopic image to a considerable degree. In the present article we shall describe an image intensifier designed in the Philips Laboratories at Eindhoven. This equipment is based on the well-known principle of the image converter, another development of this laboratory, a description of which was given as early as in 1934.

The fluoroscopic images obtained with the aid of this instrument are roughly 1000 times brighter than those produced on the ordinary fluoroscopic screen.

**Description of the intensifier**

The more important details of the unit are illustrated in fig. 1. A fluoroscopic screen on a support of thin aluminium is mounted in an evacuated glass tube. A photocathode lies in contact with the screen. When X-rays pass through the glass wall of the tube to the screen, this fluoresces. The fluorescent light sets electrons free from the photocathode; at any point on the photocathode the number of photo-electrons released per second is proportional to the luminous intensity of the fluoroscopic screen at that point. The luminous image with all its variations in brightness is thus transformed into an “electronic image” with corresponding variations in current density. By means of an electric field of a certain configuration (electrostatic “electronic lens”) this electronic image is reproduced on a second fluorescent screen, the viewing screen, reduced 9 times in size. The energy of the electrons falling on this screen is in part converted to fluorescent light, and a reproduction of the image on the fluoroscopic screen is thus seen on the viewing screen reduced 9 times. This reduced image is viewed through a simple microscope of about 9× magnification, and finally the fluorescent image is thus seen erect and in its original size (both the electronic lens and the microscope produce inverted images).

The image seen through the microscope is thus identical with that seen on an ordinary fluoroscopic screen; it is, however, about 1000 times brighter, assuming that the image intensifier and the fluoroscopic screen both receive X-rays of the same intensity.

**How is the brightness intensification obtained?**

Two factors (which are not in fact independent of each other) contribute towards the intensification of the image brightness.

The first and more readily understood factor is an increase in the total luminous flux. The electrons emitted by the photocathode are not only focused on the viewing screen by the electrical field, they are also accelerated by it; in the particular instrument under review a potential of 25 kV is applied between the viewing screen and the photocathode. The more energy possessed by an electron on arrival at the screen, the more fluorescent light it will produce. Notwithstanding the fact that only about 1 in 10 of the light quanta from the fluorescent screen liberates a photo-electron and that only some 10% of the electronic energy is converted to light by the viewing screen, the last mentioned screen — owing to the energy imparted to the electrons — is able to yield a total of 10 to 15 times as much luminous flux (in lumens) as an ordinary fluoroscopic screen, for the same object viewed.

The second, more important factor is the gain produced by the above-mentioned electron-optical...
reduction of the size of the image. All the electrons coming from the photocathode contribute towards the final image, and the energy that each electron is capable of converting to light after passing through the electron-optical system is independent of whether the electrons are distributed over a large or over a small area. By employing a reduction of 9 times we concentrate the electrons in an area $9^2$ times smaller, and the total luminous flux is thus emitted from an area that is about 80 times smaller than would be the case in reproduction on a scale of 1:1. This, by definition, represents an increase in brightness by a factor of 80.

The total gain in brightness is equal to the product of the “lumen gain” and the gain due to the reduction in size, i.e. in the tube in question, 10 to 15 times $9^2 = 800$ to 1200.

It is perhaps not superfluous to add that the gain brought about by the electron-optical reduction cannot be obtained by the ordinary methods of optical reduction. According to Abbe’s law, the apparent brightness of an object does not vary as a result of the introduction of any kind of optical instrument between the object and the eye of the observer, that is, if such an instrument can be regarded as ideal, without the absorption and reflection losses that normally occur in lenses and mirrors (and assuming the exit pupil of the instrument to be at least as large as the pupil of the eye).

This will readily be appreciated on reference to fig. 2a. Let the brightness of the object be $B$, and the solid angle subtended by the lens when seen from the object $w$. The lens then receives from a surface element $df'$ a luminous flux of $\Phi = Bwdf'$. This luminous flux is concentrated in a smaller area $df''$ in the image space. This area thus again emits the luminous flux $\Phi'$, this time, however, within the greater solid angle $w'$ (or, with diffusion, in an even larger angle). The brightness of $df''$ is $B' = \Phi / w'df''$ and, since we know from the laws of optics that $wdf' = w'df''$ (the sine law), $B'$ is equal to $B$.

The difference that is seen to exist in this case by no means implies that the analogy between electron-optics and light-optics is no longer valid. Abbe’s law as stated in the above simplified form holds good only when the object and the image are located in media having the same refractive index, and in ordinary optical instruments this is usually the case. If the refractive index of the medium containing the image is higher than that of the object, the brightness of the image can certainly be greater than that of the object itself. This is exactly what happens in electron-optics. The potential field in which the electrons are moving may be regarded as a medium the refractive index of which is continuously variable; in fact, the index is at any point proportional to the velocity of the electrons. The refractive index at the site of the viewing screen is therefore about 100 times higher than that at the photocathode.

The analogy is thus not only restored formally, but may again be illustrated in a simple way. Owing to the continuous variability of the refractive index, the “rays” are now not straight, but curved. The path of the rays in the electrostatic electron-lens therefore takes the form shown in fig. 2b, in contrast with fig. 2a; it will be seen that the flux radiated from the surface element $df$ within a solid angle almost equal to $2\pi$ is employed and is concentrated in a much smaller solid angle at the surface $df''$.

By reason of the influence of the velocity of the electrons, it is seen that the “lumen intensification” and the brightness gain due to the reduction in size virtually spring from the same cause, i.e. the presence of the accelerating field.

![Fig. 2](https://via.placeholder.com/150)

**Fig. 2.** a) Path of rays on optical reproduction of a surface $df$, at $df''$ (illustrating Abbe’s law).

b) The same, as applicable to electron-optical reproduction with an electrostatic lens, as in the image intensifier.

In the light of Abbe’s law it will now be understood why in the last stage of the image intensifier, viz. the optical enlargement by the microscope of the image on the viewing screen, the gain in brightness arising from the electron-optical reduction is not neutralised (provided that the microscope meets the condition as regards the exit pupil to which reference has already been made).

It may possibly strike the reader that in the foregoing, particularly in our explanation of the lumen gain, the luminous flux of the viewing screen is each time compared with that of an ordinary fluoroscopic screen and not, as might appear more obvious, with the luminous flux of the fluorescent screen in the image intensifier itself. The reason is that the last-mentioned screen need not be observed and that the luminosity curve of the fluorescent light emitted by it may therefore be such as to be quite unsuitable from the point of view of direct observation; in fact the fluorescent...
radiation might even be entirely invisible, for instance ultra-violet or infra-red, provided only that the photocathode be sensitive to such radiation. Our image intensifier is equipped with a photocathode the quantum efficiency of which is highest (about 10%) when it is exposed to blue light. A phosphor giving blue fluorescence was accordingly chosen for the fluoroscopic screen. For the viewing screen, on the contrary, a choice from different materials of the same luminous efficiency is available, that colour should be employed of which the fluorescent spectrum coincides as nearly as possible with the maximum in the spectral sensitivity curve of the eye. This would be a phosphor emitting yellow-green light. Clearly, if we compared the brightness of such a viewing screen with that of the blue emission of the fluoroscopic screen in the image intensifier, we would calculate a much greater brightness intensification value than 1000 times, but at the same time one that would have no practical significance.

For this reason it would be as well to dwell for a moment on the precise meaning of the name “image intensifier” or “brightness intensifier”. In effect the instrument is an image converter, which converts the “image” of the invisible X-rays to a visible image, by analogy with the well-known instruments for transforming infra-red radiations into visible images (see the article referred to in note 4) which are employed in numerous different forms. The fact that this conversion in our case involves as intermediate stage a visible fluorescent image (as in normal fluoroscopy) is attributable only to the impossibility of liberating photo-electrons directly from a photocathode with any degree of efficiency (and with not too high an initial velocity) by means of the X-rays themselves. Reasonable efficiency in this release of electrons is naturally of the highest importance in the fluoroscopic image intensifier, as otherwise the effect of the subsequent gain would be lost and we might then just as well employ only the “image conversion” as obtained from the ordinary fluoroscopic screen.

Details of construction

The blue fluorescence of the fluoroscopic screen as matched to the photocathode is obtained from zinc sulphide activated with silver, and the yellow-green fluorescing viewing screen is prepared from very finely divided zinc sulphide-zinc selenide. The effective diameter of the cathode face is 13.5 cm, this thus representing the maximum size of the object to be examined. The image on the viewing screen is only 1/9th of this size, viz. 1.5 cm across.

The electrical field producing the electron-optical image is generated basically by means of only two electrodes, one of which (the cathode) is formed by the concave spherical surface of the combined fluoroscopic screen and photocathode, as well as by a conductive layer on the inside wall of the glass tube. The other electrode (the anode) is also spherically curved and is concentric with the photocathode; it has in it an aperture to allow the electrons to pass to the viewing screen behind it 6). Between the cathode and the anode a potential of 25 kV is applied.

This simple design, employing only two electrodes, has proved to be very effective. Definition in the image is ample and the field strength on the only slightly curved photocathode is very low, this being an asset for a reason which is given in another paragraph. When the tube was still in the experimental stage, the configuration offered sufficient latitude, viz., in the radii of curvature of cathode and anode, allowing for example a variation in the amount of reduction of the image. For practical purposes it was later found to be better for the inner lining of the tube to function as a separate electrode and to maintain it at a slightly positive potential with respect to the photocathode. Without this, only the electrons emitted from the central part of the photocathode pass through the opening in the anode, the peripheral parts thus not being reproduced. With the auxiliary potential applied the peripheral electrons also pass through the anode, the effective image area of the fluoroscopic screen being thus almost doubled. At the same time, the slight “pin-cushion” distortion of the image that occurs without the auxiliary voltage is in this way almost entirely eliminated. Another important advantage of the auxiliary potential — which is variable — is that by means of it the image on the viewing screen can be adjusted for maximum definition whilst the tube is in use. Consequently, the tolerances in the electrode spacing, during the manufacture of the glass tube, can be relatively wide.

The 25 kV applied between cathode and anode may be obtained for instance from the well-known small high-tension generator developed in this Laboratory for projection television 7). This generator also supplies the necessary voltage for the inner tube coating. The cathode is earthed, so that only one of the three poles of the image intensifier need be suitable for carrying high voltage. Only a very small amount of power is required to operate the tube, the photo-current for normal fluoroscopy being in the order of 10⁻⁹ A. For this reason and also in view of the fact that in this case no stringent con-

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6) For a more detailed description of the principle of this two-electrode lens the reader is referred to an article by P. Schagen, H. Bruining and J. C. Francken, Philips Research Reports 7, 119-130, 1952 (No. 2).

ditions need be imposed as regards voltage stability (a basic advantage in purely electrostatic electron-optical systems), an even simpler high-tension unit would suffice.

Fig. 3 depicts the complete image amplifier tube. It is cylindrical, the diameter being 17.5 cm; the over-all length, including the small microscope, is 45 cm. To protect the tube against jarring and to afford local protection from stray X-rays, the tube proper is contained in a lead-lined aluminium jacket which can be mounted quite simply on a stand; see fig. 4. Tube and jacket together weigh 7.5 kg approx.

**Definition and contrast in the image**

When the image intensifier is in use it is not necessary for the radiologist to allow time for his eyes to adapt themselves; examinations can be made in a room with almost normal illumination. This is in itself a great practical advantage that will almost certainly outweigh the drawback that the image cannot be surveyed with the naked eye, but only through an optical system. Moreover, it may be expected, as explained in the introduction, that the radiologist will be in a position to perceive smaller details than is possible with the ordinary fluoroscopic screen because of the higher visual acuity and contrast sensitivity of the eye at the increased brightness level. In order that this expectation — which we shall elaborate upon presently — may be realised, it is an essential condition that the blurring and loss of contrast introduced by the image intensifier itself, as by any other form of optical instrument, shall be kept within certain limits.

**Definition**

In normal fluoroscopy the definition of the image will be determined by the finite dimensions of the focus of the X-ray tube (half-shadow width or geometrical blurring) as well as by the thickness and grain size of the fluoroscopic screen (intrinsic or screen blurring). Screen blurring is usually about 0.7 mm, sometimes less, down to 0.4 mm; the geometrical blurring is generally slightly less. The resulting definition in the fluoroscopic image is thus somewhat less than 1 mm (the total blurring being equal, approximately, to the square root of the sum of the squares of the geometrical blurring and the screen blurring 8)).

Screen blurring can be reduced considerably by using thinner screens (and finer grain). This is not done in the case of ordinary fluoroscopy, as such screens would transmit a larger amount of X-rays, which are thus ineffective, resulting in reduced screen efficiency 9). Moreover, better definition would be

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9) As far as efficiency is concerned there is an optimum thickness, for in screens that are too thick, apparently too much absorption of the emitted light will take place in the screen itself. (This conflict between useful absorption of the incident radiation and wasteful absorption of the rays emitted in the image intensifier again occurs in the photocathode and in the viewing screen.)
of little use, since, at the low brightness levels of normal fluoroscopic screens, visual acuity is in any case too low for the perception of finer detail.

In the image intensifier the position is very different. Here, too, there is a primary lack of definition in the image owing to the intrinsic blurring in the fluoroscopic screen employed. However, there is now no objection to the use of a relatively thin screen, thus sacrificing some of the gain in brightness to benefit the definition.

The grain size of the viewing screen used is very fine and the screen itself very thin (the penetration depth of electrons at 25 kV is about 12 μ), so that the intrinsic blurring in this screen, referred to natural image size, is less than that of the fluoroscopic screen. Blurring by the electron-optical reproduction system is at least one order of size less (see formula (26) in the article referred to in note 6)) and can therefore be ignored, as can, also, the limitation in the resolving power of the microscope through which the screen is viewed. No appreciable blurring occurs in the photocathode either, since this is in direct contact with the fluoroscopic screen, and, in order to avoid too much absorption of the liberated photo-electrons, is extremely thin.

Owing to these favourable properties, the over-all blurring effect produced by the image intensifier is not more than 0.4 mm. In order that the advantage of this low "intrinsic" blurring may not be lost, the previously mentioned geometrical blurring must also be limited as much as possible. It is therefore desirable to use in conjunction with the intensifier an X-ray tube having a very small focus (fine focus tube).

A real advantage is obtained by so doing, for the visual acuity at the brightness level of the image intensifier is so high that the eye can reap the benefit of the increased definition.

For this reason a thinner fluoroscopic screen is used in the image intensifier than is provided for ordinary fluoroscopy. On the other hand the reduction in the screen thickness cannot be carried too far, for a reason other than that connected with efficiency, as will be seen presently.

In the case of the image intensifier there are also other possible causes of blurring. These must of course not detract from the available gain in definition, and in fact, in our model, they do not.

Fig. 4. The complete equipment for fluoroscopy by means of the image intensifier. The tube is housed in a lead-lined aluminium jacket and the whole can be conveniently mounted on a stand. Left: the small high-tension unit for supplying the necessary 25 kV, D.C.
Contrast

On passing through the subject to be examined, the X-rays are attenuated to an extent that varies from one point to another, and it is the resultant "radiation contrast" that supplies the required information regarding the subject, i.e. the image. The processes involved in the conversion of the X-rays to fluorescent light, then into photelectrons and finally into light again, are wholly linear, owing to the very small electronic current occurring in the image intensifier. In principle, therefore, the contrasts in the image are unchanged (gamma = 1), in contradistinction to, for example, photographic reproduction (in which case gamma may be as much as 2.5 to 3).

For various reasons, however, the image intensifier does occasion a certain amount of fogging, i.e. a brightness contribution more or less uniformly distributed over the whole image, which results in a loss of contrast. The glass window of the tube through which the X-rays enter partly scatters the rays and thus delivers diffuse radiation to the fluoroscopic screen; similarly those X-rays which are not absorbed by the fluoroscopic screen but which fall on the wall of the tube are in part re-diffused towards the screen. Again, a fraction of the blue fluorescent light which the very thin photocathode is not capable of absorbing is reflected from the inner wall of the tube, back to the photocathode, where it liberates electrons in the wrong places; up to a point this also applies to the persistence of the fluorescent screen. Furthermore, the photocathode exhibits a certain amount of thermionic emission which is independent of the intensity of illumination received by it; field-emission is also liable to occur at the photocathode. Both these effects contribute additional light uniformly spread over the whole of the viewing screen. A proportion of the total number of electrons arriving at the viewing screen is reflected there and tends to liberate positive ions from the walls of the anode space (as well as from possible residual gases), and these ions may be diffused in the direction of the anode aperture where they are accelerated by the field in the direction of the photocathode; here they may liberate more electrons and this will also produce additional diffuse light. Finally, at the viewing screen there is also some diffusion of the light generated by the screen itself, resulting in a kind of halo which is intensified by repeated reflection in the glass support of the screen, whose granules are in contact with it.

Very severe fogging would occur if a part of the light from the viewing screen were to return to the photocathode (a kind of "feedback"), but this is prevented by coating the rear of the viewing screen with a thin layer of aluminium which transmits practically all the high-velocity electrons, but completely intercepts light that would be reflected back�).

Suitable precautions have also been taken to reduce to a minimum all the other sources of fogging summarised above. As a result the loss in contrast is kept within reasonable limits. We will mention only one or two of these precautions. For example, the inner lining of the tube is of a kind that does not reflect blue light too well. The shape of the electrodes is such that high field strengths do not occur at the photocathode, and field emission is accordingly low. For the same purpose and also in order to limit thermionic emission, the threshold potential of the cathode should be fairly high.

Accurate data regarding the degree of fogging cannot be given at this time, but for orientation purposes we may assume that this represents 10% of the total luminous flux which the viewing screen would emit without the fogging. (This value is probably not very far from the actual figure.) From the aspect of contrast this means that where we would have had to observe contrast between a brightness of 105 and an average of 100 for example, we will now have a contrast of 115 : 110. The loss is thus of little importance. When contrast is very pronounced the depreciation is greater (10 as against 100 would become 20 to 110), but such contrasts are generally easily distinguished in any case.

Principle limitation of minimum perceptible subject detail

Let us now ascertain in how far the radiologist, using the image intensifier, really will be able to perceive more detail, that is, details of smaller dimensions and lower contrasts, than with the ordinary fluoroscopic screen. The ultimate answer to this question can be obtained only with the intensifier in actual use. While, however, insufficient medical experience has been gained as yet with the instrument to enable one to express in numerical values the advance which the introduction of the intensifier undoubtedly represents, it is possible to show theoretically that the minimum detail to be perceived cannot decrease below a certain limit. This is attributable to the circumstance that X-rays are in the form of quanta; attention was first drawn to this consequence by the scientists Sturm and Morgan�).

The energy quanta, or photons, of magnitude
$hv$, of which all radiations consist ($h =$ Planck's constant and $v =$ frequency of oscillation), are not emitted by the source perfectly regularly, nor are they absorbed regularly by a medium such as the fluoroscopic screen or the retina of the eye. It is possible to speak of an average number $N$ of quanta per given interval of time, on a given surface, and this determines the intensity of the radiation emitted or absorbed. In the case of a number of such time intervals, however, the number of quanta within each interval will not be equal to $N$; random fluctuations about this average occur, whose order of magnitude, computed on the basis of probability, is given by the so-called standard deviation $\sqrt{N}$. The order of magnitude of the relative fluctuations in the radiation is defined by the coefficient of variation, which is equal to $\sqrt{N}/N = 1/\sqrt{N}$.

These natural fluctuations, the "noise" in the radiation, set a fundamental limitation on the detail which the radiation is capable of conveying, or, in more concrete terms, on the minimum radiation contrasts which can be communicated by means of the quanta absorbed.

This argument is immediately applicable to the human eye. Let us take as starting point a surface element of a given object, with a size of 0.1 mm$^2$. Those quanta will contribute towards the perception of brightness which travel from this surface element to the pupil of the eye within the "accumulation time" $T$ of the eye. Only a fraction of these is effectively absorbed in the retina, i.e. produce the stimulus conveyed to the brain by the optic nerve. The fluctuations in this number of quanta can be regarded as fluctuations, in effect, in the observed brightness of the surface in question, and it is found that the difference in brightness between this surface and its background definitely cannot be perceived if the contrast is not at least 3 to 5 times as great as the relative fluctuation already mentioned. The lower limit of perceptible contrast is thus expressed in terms of the "noise" in the light quanta effectively absorbed. It will now be seen at once that as the size of the surface observed is increased (i.e. more quanta are permitted to contribute to the sensation of brightness), so also does it become possible to appreciate lower contrasts; see for instance the well-known contrast-detail diagrams obtained in the fluoroscopic examination of phantoms (artificial test-objects), fig. 5 [12]. It will also be clear that when the brightness level is raised, contrast sensitivity increases.

However, this takes place more slowly than might be concluded from the decrease in the relative fluctuations, since, when the brightness increases, the percentage of light quanta effectively absorbed drops (owing amongst other things to a saturation effect in the optic nerve), as also does the accumulation time $T$.

![Fig. 5. Example of a contrast-detail diagram as obtained with the aid of an X-ray "phantom". The "phantom" consists of a number of plates of "Philite", one of which has in it a number of holes of different diameters and depths. The full line represents as a function of the hole diameter, the depth of a hole (contrast!) necessary to make it just visible in normal fluoroscopy. (The dotted line shows the results of provisional tests with the image intensifier under the same conditions.)](image)

Let us now turn to X-ray diagnostics, again taking a surface of 0.1 sq. mm of the fluoroscopic screen. In chest examinations 100 000 X-ray quanta fall on such an area per second. Of this the fluoroscopic screen absorbs 65%. The accumulation time $T$ of the eye in normal fluoroscopy is about 0.1 sec. The number of X-ray quanta involved in providing information about details of the above-mentioned size of the lungs under examination is therefore about 6500. One X-ray quantum of 70 kV absorbed liberates an average of 5000 light quanta in the screen. Thus we have more than $3 \times 10^7$ effective quanta; these occur in "packets" of 5000 quanta at a time, however. Consequently — and this is the cardinal point of the whole argument — the large number of quanta that would yield the low relative fluctuation of 1/5600 (if all the quanta occurred individually) cannot furnish any more information than the original 6500 X-ray quanta were capable of doing, with the much greater fluctuation of 1/80.

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In normal fluoroscopy this is not really important. In fact, of the light quanta obtained, only a very small proportion falls on the pupil of the eye (see fig. 6): in the retina only 120 quanta are effectively absorbed, which is much less than the available number of X-ray quanta. In X-ray images of objects 0.1 sq. mm in size, therefore, the eye will not perceive contrasts of less than 3 to 5 times 1/11 and a large part of the information contained in the X-ray quanta is thus not used.

The image intensifier, however, has entirely altered this state of affairs. Initially the situation is rather less favourable, since, out of the above mentioned 100 000 X-ray quanta falling per second on 0.1 sq. mm of the thinner fluoroscopic screen, fewer are absorbed by the thinner screen and, moreover, the accumulation time \( t \) of the eye is shorter at the higher brightness level of the intensifier. We may take the number of effectively absorbed quanta to be about 1750. The light quanta produced by them in the fluoroscopic screen, however, are now put to better use (see fig. 6); it may be estimated that the area observed now yields roughly 20 000 actively absorbed light quanta, which is considerably more than the number of active X-ray quanta. This means that contrast sensitivity is then high enough for the eye to register the whole of the information contained in the X-ray quanta — but, obviously, not more.

This bears a direct analogy with optical enlargements. For example, in the image produced by a microscope objective, the fine details of the object are resolved only up to a certain limit; the “information” regarding the object is limited by the resolving power of the objective (which is in turn determined by the lens aberrations and ultimately by the wavelength of the light). The resolving power of the eye is much lower and the image is therefore observed through a high-magnification eye-piece. Now the greatest effective magnification of the eye-piece is that at which the details as separated by the objective can be seen as separate by the eye. If the eye-piece is any stronger, the details are certainly seen at larger angles, but the wealth of detail is not increased, the information contained in the image being by then already exhausted. It may be said that the extra enlargement is “ineffective”. Similarly it may be said of the image intensifier that the part of the brightness intensification which corresponds to the factor by which the number of effective light quanta in the eye exceeds the number of effective X-ray quanta in the fluoroscopic screen, may be regarded as ineffective.

The conclusions to be drawn from the above argument are as follows:

1) Of the brightness intensification factor of 1000 which our instrument yields, a maximum factor of about 20 is “effective” \(^ \text{13} \); the remaining factor of 50 plays no part in reducing the smallest perceptible contrast, but is of great practical significance as it makes vision easier (no adaptation necessary).

2) Should it be found desirable to make use of the properties of the image intensifier to reduce the X-ray dosage to the patient (for the same duration of observation), this will be unavoidably

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\(^ {13} \) This factor is greater than the ratio 1750/120 to be derived from the example in fig. 6 since, owing to the decrease in the accumulation time \( T \), as also in the percentage of quanta producing stimuli in the optic nerve, a relatively higher brightness is required to ensure that the eye absorbs as many effective light quanta as there are effectively absorbed X-ray quanta.
accompanied by a loss of "information" which is, after all, determined by the number of X-ray quanta. If the same amount of information as that obtained from the ordinary fluoroscopic screen is considered adequate, the dosage for the purpose of a chest examination could, theoretically, be reduced at most to about 1/15th; this would still leave in hand a gain in brightness to a factor of about 60, which would represent a marked decrease in adaptation time. For thicker subjects the permissible reduction factor would be smaller.

The image intensifier and radiography

Similar considerations to those outlined above will make it clear that the use of the image intensifier can never provide the same high quality of image as that obtained in X-ray photography (radiography). The photograph owes its superiority to the fact that the accumulation time of the photographic emulsion is not limited, as is that of the human eye, added to which the emulsion retains what it has accumulated, the dosage time being thus no longer than the accumulation time. Unless a series of exposures is to be made, the dosage is therefore not usually dangerous and the intensity of the X-rays and/or the exposure time can be adjusted for each subject so as to yield the best average density. For a representative grade of film it will be found that to this end 20 000 X-ray quanta per 0.1 sq.mm (about 0.001 ergs of energy) must be effectively absorbed. The exposed film is examined with the aid of a viewing lantern; the illumination level can be raised as desired and matters so arranged that the light quanta received by the retina are in any case sufficient for perception of all the information the photograph has to offer (fig. 7). Now the difference in image quality between normal fluoroscopy, image intensifier and radiography is immediately expressed by the difference in number of useful quanta, i.e. for a chest examination 120 : 1750 : 20 000. With subjects that entail a higher degree of absorption (e.g. gastric fluoroscopy), the supremacy of the photograph is still more pronounced; it remains at 20 000 quanta, whereas in the two other cases the numbers of quanta are much lower.

Under these circumstances it will be obvious that the principle of the electronic image intensifier has no advantage over conventional X-ray photography. It can be employed to advantage, however, in fluorography. In this Review, on several occasions, the fact has been discussed that in this technique, whereby a reduced X-ray image is obtained with the aid of a camera, it is a difficult matter to obtain sufficient light to expose the film, and this is the reason why extremely fast lenses have been developed for this class of work 14). The image intensifier, which furnishes a very bright, reduced image that is capable of being photographed quite easily on a 1 : 1 scale, provides a very convenient solution to the problem. Apart from this, the image intensifier may possibly prove to be the answer to the old problem of X-ray cinematography. As far as the mechanical aspect is concerned, X-ray fluorography has already brought a solution within sight, but the next step towards successful X-ray cinematography, although apparently only a small one, calls for some caution, since a very large number of photographs taken in succession means that the total X-ray dosage to the patient will again be fairly high. A reduction in the X-ray intensity with a view to limiting the total dosage

Fig. 7. Same as in fig. 6 but for normal radiography (dotted line). Full line; with image intensifier, as reproduced from fig. 6.

14) W. Hondius Boldingh, Fluorography with the aid of a mirror system, Philips Techn. Rev. 13, 269-281, 1952 (No. 10).
during the taking of the film is possible only up to a certain point, seeing that even with very fast lenses too little light is otherwise obtained to ensure sufficient density of the film. This difficulty is overcome by the extra brightness provided by the image intensifier; even at appreciably lower X-ray intensities than those usually employed in fluoroscopy, the image on the viewing screen will ensure a well-exposed film without necessitating particularly fast lenses. The fact that a reduction in the X-ray intensity detracts from the image quality (available information) has already been explained. It is a well-known phenomenon, however, that some slight sacrifice in image quality can safely be made in cinematography, since the summation of the impressions received from the successive pictures provides additional information.

Summary. In order to reduce to a minimum the risk of injury to the patient as a result of X-ray examination, the X-ray dosage that the patient receives must be limited as far as is practicable. Therefore, the attainable brightness of the image on a standard fluoroscopic screen is so low that long visual adaptation periods are required before such images can be studied; even then, visual acuity and the contrast sensitivity of the eye are both fairly low at such low brightness levels. Improvement can be brought by increasing the brightness of the fluoroscopic image ("intensifying"). The electronic tube by means of which this is now made possible functions on the principle of the image converter. The X-rays produce on a fluoroscopic screen an image whose radiation liberates electrons from a photocathode in contact with the screen. The electrons are focussed by an electrostatic electronic lens system working at a potential of 25 kV, to produce another image, reduced 9 times in size, on a second fluorescent screen, the viewing screen, which is observed through a simple microscope of 9 X magnification. The gain in brightness, to a factor of 800-1200 with respect to normal fluoroscopy, is produced partly by the accelerating field which imparts energy to the electrons, and partly by the electron-optical reduction of the fluoroscopic image. The resolving power of the image intensifier is higher than that of the best fluoroscopic screen. Owing to a number of causes the ultimate image is subject to a certain amount of fogging, which does reduce the contrast, although not to a serious degree. From a discussion of the lower limit of perceptible detail as based on spontaneous fluctuation in the number of X-ray and light quanta it is seen that the brightness can be intensified up to a factor of about 20 with a corresponding increase in the amount of "information" to be derived from the image. Beyond that point the information is restricted by the number of contributing X-ray quanta, but the much higher gain factor of the image intensifier offers the advantage that the image can be viewed without preliminary dark adaptation of the eyes, in a room with practically normal illumination. In conjunction with film cameras the intensifier paves the way to X-ray cinematography without the necessity for increasing the X-ray dosage to a hazardous extent.