Fluoroscopic Image Brightening by Electronic Means

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More than six years have passed since Dr. W. Edward Chamberlain delivered the annual Carman Lecture before the Radiological Society of North America. In this lecture (1), he described in great detail the limitations of present-day fluoroscopy, and held out hope that these severe restrictions might soon be removed, or greatly alleviated, by the application of modern electronic technics to the amplification, or brightening, of fluoroscopic images. Such amplification has recently been accomplished in the Research Laboratories of the Westinghouse Electric Corporation, and it is hoped that before long practical realization of the method for use in clinical fluoroscopy will become available to the radiologist.

There are two reasons why image amplification, or brightening, is necessary if large increases of brightness are to be obtained. First, x-ray intensities are already at the patient's tolerance level and may not be further increased without danger of injury. Second, there is not sufficient energy in the emerging x-rays to form an adequately bright picture even if all the energy were converted into light.

Image amplification has been achieved by converting the x-ray pattern into an electron stream, and accelerating these electrons to high velocities. In this way, energy from an external source is introduced into the system and, when the electrons impinge on a phosphor layer, a brighter image results. This paper deals with the technical aspects of fluoroscopic image amplification, and describes in some detail the mechanism just outlined.

Were it not for the dimness of the image, fluoroscopy would replace to a large extent the taking of roentgenograms. A single fluoroscopic examination would be equivalent to hundreds of films taken in cinematographic sequence and revealing the subject in all phases of movement and from many angles of projection. Unfortunately, however, the fluoroscopic image is excessively dim, and at existing brightness levels the human eye is capable of perceiving only a fraction of the detail which is actually on the screen. Dr. Chamberlain covered this aspect of the problem very thoroughly, and it will suffice to present here only a few aspects of retinal physiology which will serve to illustrate the tremendous ranges of brightness over which the eye is adaptable, and the great loss of definition which is incurred at low levels.

The brightness level at which roentgenograms are ordinarily viewed is roughly 30 millilamberts. At this level, the eye is capable of recognizing as discrete two contours which are separated by as little as one one-thousandth of an inch. As the brightness of the object is decreased, the visual acuity of the eye deteriorates. At about one thousandth of this intensity we have reached the point where cone vision is no longer effective, the color sense is gone, and the fovea centralis is no longer the most sensitive part of the retina. Only rod vision is now present, and visual acuity is such that two contours must be separated by about 1/64 inch to be distinguishable. But we are still a long way from fluoroscopic levels. At a brightness of 0.001 millilamberts (1/30,000 of the brightness of the film mentioned above!) we are in the middle of the fluoroscopic range, and we find the contour separation required is about 1/32 inch.

For the worst cases, *i.e.*, extreme abdominal thicknesses, the brightness may approach 0.00005 millilamberts, and the necessary contour separation 1/4 inch. Even this poor result does not describe the full extent of our difficulty, since it refers to an idealized situation not realized in fluoroscopy. Discrimination between neighboring areas is largely a function of the difference in their brightness, *i.e.*, a function of contrast, and contrasts occurring in fluoroscopy are rather low. Whereas a difference in brightness of 1 or 2 per cent proves to be distinguishable at brightness levels used for reading, it may take differences of 20 to 40 per cent to accomplish the same discrimination at fluoroscopic brightnesses. Thus the low contrasts common in fluoroscopic images will result in a further lowering of our visual acuity. The quoted values for needed contour separation above were obtained in measurements where the contour lines separated regions with a contrast of 100 per cent *i.e.*, contours between black and white. Clearly, such separation will be insufficient where the contrast is considerably less than 100 per cent.

Even these poor visual acuities can be acquired only by resorting to long periods (at least twenty minutes) for dark adaptation of the eye. Too short an adaptation time will greatly decrease the ability of the eye to perceive small objects.

Though x-ray equipment is now available which would permit much higher intensities than those used in conventional fluoroscopic equipment, such dosages would be injurious to the patient, whose tolerance to exposure now sets the limitation for attainable brightness of the fluoroscope image. A large increase in brightness without an increase in x-ray intensity, is thus needed to make up for the shortcomings of the viewing eye. While the fluoroscopists, in an effort to improve a desperate situation, would welcome a doubling of the present brightness, increases of an entirely different order of magnitude are necessary to make full use of the information which is actually contained in the fluoroscopic image. To achieve fluorescent images at all comparable to roentgenograms, increases of 100- to 1,000-fold are necessary. It is evident then that we must turn our attention to the x-rays after they have left the patient, and examine the possibilities for converting into a bright visible image the intelligence which they convey.

The present-day fluoroscopic screen is a rather remarkable device. Measurements indicate that it may convert into visible light 30 per cent of all x-ray energy absorbed in the screen. Unfortunately, only about 15 per cent of the incident x-rays are absorbed, the rest passing through without effect. In addition, there is some loss of light within the screen, so that the gross efficiency turns out to be about 3 per cent.

It is perfectly possible that more efficient fluorescent materials may be available in the future, and that some improvement can be made in the absorption. However, a theoretically perfect fluorescent screen would be only about thirty times as bright as the present screens, and it seems unlikely that any material even approaching this figure will be forthcoming. If we wish to achieve gains of 100 to 1,000 there is only one avenue left—the x-ray pattern after it leaves the patient must be used to operate some kind of amplifier which injects into the system energy from an external source.

Before entering into a detailed discussion of how this may be accomplished, it would be well to have assurance that the fluoroscopic image does actually contain sufficient additional information to make amplification profitable. This is by no means obvious. While it is true that fluorescent screens are being used as intensifiers for roentgenograms and succeed in providing a wealth of detail not apparent to the unaided eye, this performance is not in itself a fair basis for drawing a conclusion. The difference lies in the times of exposure. To view objects in normal motion on the fluoroscopic screen, we must present to the eye a complete new image about every twentieth of a second, *i.e.*, roughly the frame period for satisfactory motion picture presentation. Total x-ray exposure during this time interval amounts to 0.05 second × about 5 ma. (a normal fluoroscopic tube current), *i.e.*, about 0.25 milliampere second. Now a roentgenogram of a normal abdomen may require an exposure of about 80 milliampere seconds. It is a pertinent question whether it is not over-optimistic to expect comparable quality in the two cases. Actually, there is a good physical reason to suspect that perhaps, under these conditions, the initial x-ray pattern is not complete. The x-rays emanating from the tube are not continuous; as is well known, they consist of quanta or packets of energy, behaving in general as discrete particles. If one had a theoretically ideal x-ray film, and exposed it to x-rays for a very short time, one would expect the developed picture to be made up of small dots, each dot representing the place where an x-ray quantum had struck the film. The dots would be scattered at random over the film, except for greater concentrations corresponding to the thinner portions of the object through which more x-ray quanta had passed. It is seen that this picture would have an incompleteness owing to the quantum nature of the x-rays themselves. No amount of magnification or increased illumination of the film could fill in the missing information.

In practice, this phenomenon is never observed, for our x-ray films have a threshold exposure below which no blackening will take place, and long before this threshold is reached a number of quanta have been collected which is so great that other factors (such as film grain) mask out the quantum "dots." Likewise, fluoroscopic images are so dim that the eye cannot perceive the individual scintillations which really exist on the screen. Nevertheless, if we attempt to amplify the brightness of these images by very large factors, so that the eye is no longer a limitation, we will find that quantum scintillations set an upper limit to the quality of the picture which cannot be exceeded, and one must ask if this limit is not so low as to interfere seriously with our purpose.

This problem was first pointed out by Dr. R. C. Mason of the Westinghouse Research Laboratories, who made a series of calculations as to the magnitude of the effect. This calculation indicated that scintillations would be definitely perceptible at high amplification, but it was very difficult to estimate the extent to which they would interfere in creating a visual impression in the eye and mind of the observer. An experimental arrangement was therefore set up to test directly the effect of scintillations on the visual acuity and intensity discrimination of the eye. By methods similar to television presentation, a test pattern made up of randomly scintillating dots was projected on the face of a cathode-ray tube. This pattern corresponded to a very weak fluorescent image amplified in brightness by a factor of 10,000. Tests made on several observers showed that the scintillations did interfere to some extent, but that they caused only a small decrease in the effectiveness of image amplification. It is important to keep in mind, however, that this is the fundamental limitation in image amplification, and that any system which does not make the fullest possible use of the available x-ray quanta incurs a deterioration of the image which cannot be corrected by subsequent amplification.

The production of images by the acceleration of electrons from a photosensitive surface was first described by Holst and others (2), who constructed an "image transformer" using this principle. A number of other investigators (3) have contributed to the subject in recent years, and the late war saw an intense development, both in this country and in Germany, of image tubes for use with infra-red illumination.

Of several systems considered, the one which seemed to offer the most advantages is shown in the diagram of Figure 1. A pilot model was first produced as shown in Figure 2. The x-rays are allowed to fall on the fluorescent screen (*1*), which is mounted in contact with the window in the end of the tube. On the inner surface of this window is a photoelectric layer (*2*) of the transparent type, that is, light entering the surface from one side ejects electrons from the opposite side. These electrons are accelerated by a high potential placed across the highly evacuated tube, and are focused by a constant magnetic field ap-

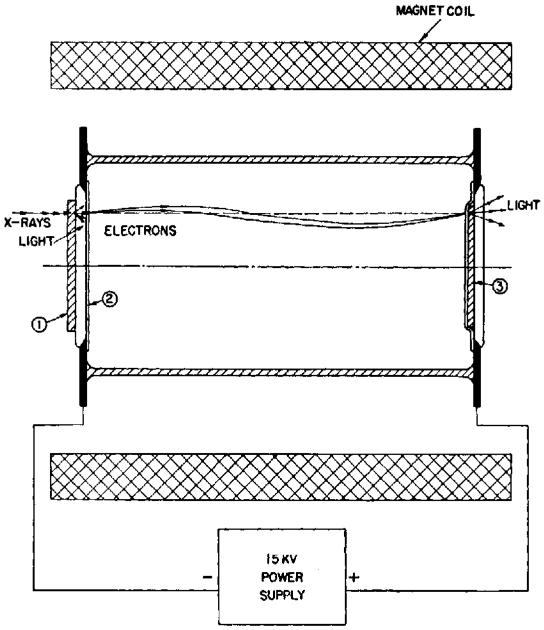

Fig. 1. Diagram of the pilot model operation. X-rays striking the fluorescent screen (1) produce light photons which eject electrons from the photoelectric surface (2). These are accelerated by the electric field from the 15-kv. power supply and focused by the magnetic field of the coil so as to form an image on the output phosphor (3). This image may be twenty times as bright as that from the conventional fluoroscopic screen.

plied axially. The electrons impinge on a phosphor layer (*3*) on the opposite end, where they form an image identical to the original pattern. If the efficiencies of the fluorescent screen, the photoelectric surface, and the phosphor are high enough, and sufficient accelerating energy is supplied, a gain in brightness will result.

Though this process is simple in principle, its success depends very much on the properties of the materials used. First we must make sure that we utilize as many as possible of the available x-ray quanta, for failure to do so will result in the loss of detail which cannot be restored by any subsequent amplification. Thus we require that the absorption of a single x-ray quantum in the screen ultimately results in the ejection of many electrons from the photoelectric surface. Thirty per cent of the energy of an x-ray quantum may be transformed into light by the fluorescent material. Now this light is also composed of quanta, or photons as they are often called, similar to the x-ray quanta except that they contain a very much smaller amount of energy per quantum. Specifically, the energy in any quantum is inversely proportional to the wave length of the radiation which it represents. Since the wave length of x-rays in the fluoroscopic range is about 0.2 Angstrom units, and the wave length of the light from the screen is about 5,000 Angstrom units, each x-ray quantum contains 25,000 times as much energy as each light quantum or photon. If the efficiency of the fluorescent process is 30 per cent, about 7,500 light quanta will be generated by a single x-ray quantum. Not all of these light quanta can be utilized, for many of them are lost before they emerge from the surface of the screen. Furthermore, only a fraction of these photons will eject electrons from the photoelectric surface. The most efficient photosurface known, and the one employed in this tube, is a compound of cesium and antimony. This surface, if properly prepared, may have a quantum efficiency of about 1/10, that is, on the average one electron is ejected for every ten incident photons. Taking this loss into account, we end up with an average of about 450 electrons for each initial x-ray quantum absorbed. From a statistical standpoint this is quite satisfactory, for even though the number of electrons ejected will fluctuate somewhat from one x-ray quantum to the next, this fluctuation will not be very large, and we shall be almost certain to utilize effectively each x-ray quantum absorbed.

The electrons thus ejected from the photosurface must be focused to give a sharp image when they impinge on the phosphor at the viewing end of the tube. In the pilot model this was accomplished by the uniform magnetic field from a coil surrounding the tube. Under the influence of the uniform electric accelerating field (supplied by the potential difference between the ends of the tube) and the uniform magnetic field, electrons leaving a point on the photosurface will describe helical paths about a line parallel to the axis of the tube. These helices, though of varying diameter, will intersect this line at the starting point and again at some other point down the line. By adjusting the relative strengths of electric and magnetic fields, this second intersection may be made to take place at the plane of the phosphor. Thus the paths of all electrons leaving a point on the photosurface converge to a point on the phosphor layer, and a sharp image is produced.

In such a system it is important that the light produced by the output phosphor be prevented from traveling back to the photosurface. If this were not done, an unstable situation might develop, whereby light from the output phosphor would return to produce electrons from the photosurface, these electrons would produce still more light, and eventually the whole system would "run away." This "feedback" can be effectually prevented by backing the output phosphor with an extremely thin membrane of aluminum. The aluminum is made thin enough to permit electrons to penetrate it with little loss of energy, and still be opaque to light. At the same time the aluminum performs two other functions: it brightens the image by returning to the observer light which would normally be lost from the back of the layer, and it maintains the phosphor layer at the desired electrical potential.

The fluorescent screen selected for use in the pilot model is prepared from a zinc sulfide phosphor similar to the type used in screens for miniature radiography. This screen has a very high intrinsic efficiency, and fluoresces in the deep blue and near ultraviolet where the cesium antimony photosurface is most sensitive. The output phosphor is a zinc cadmium sulfide phosphor similar to the usual fluoroscopic screen material, but it has a much finer crystal size. The fluorescent color of this layer is very nearly that for which the eye has maximum sensitivity.

A very great technical difficulty had to be met because of the chemical nature of the materials used in the tube. The zinc sulfide phosphors are very susceptible to impurities, and the cesium vapor used in making the photosurface, being highly active, would attack the zinc sulfide readily. In order to alleviate this problem somewhat, the fluorescent screen in the pilot model was placed outside the tube. The relatively thick glass window separating the screen and the photosurface lowered the resolving power so that the tube was of no practical value, but this did not interfere with measurements of the brightness gain.

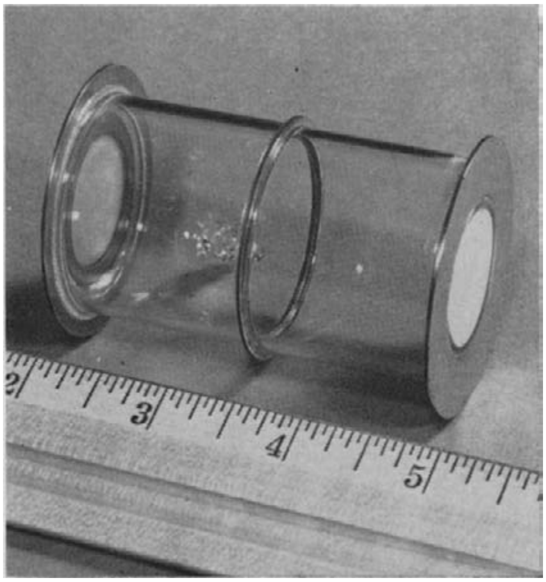

Fig. 2. Photograph of the pilot model first produced.

Because the color of the first fluorescent screen is not the same as that of the output phosphor, it is of doubtful meaning to quote brightness gains in the tube itself. A more significant procedure is to compare the brightness of the final image on the tube to that of a Patterson "B" fluoroscope screen under the same x-ray conditions. Though this does not measure a unique property of the image tube, it is a direct measure of the practical results obtained. On this basis the pilot model shown in Figure 2 had a measured brightness gain of five times when operated at 13 kv. accelerating potential. The photosurface in this particular tube did not have the high sensitivity which had been attained in some previous experiments.

From these earlier experiments, it was calculated that a properly constructed tube run at somewhat higher potential would be capable of delivering an image twenty times as bright as that from a Patterson "B" screen. Though this is a significant advance, it is still quite a distance from the desired goal. It would, however, be feasible to repeat the process in a second stage similar to the first, and achieve thereby a total gain of 400.

For the model now under construction it was decided to make use of a new principle which affords a further factor of 25 in the brightness gain, and brings with it a number of other advantages. If the image size in an electron optical system is reduced, the brightness is increased in inverse proportion to the area. This follows from the fact that all of the electrons are employed in forming the image; if the area is reduced and the total energy remains constant, the energy per unit area (which is proportional to brightness) must go up. Remarkably, if one examines this reduced image through an ordinary optical magnifier, it will appear again in its original size and yet will not lose the brightness gained in the electron-optical reduction. There is a limit, of course, to the optical magnification which can be obtained without sacrifice of brightness. In the terminology of optics, the exit pupil of the magnifying system must be kept larger than the pupil of the eye if no brightness is to be lost. As a consequence of this, it turns out that it is not profitable to reduce the size of the electron image to less than one fifth that of the x-ray image, for the contemplated design.

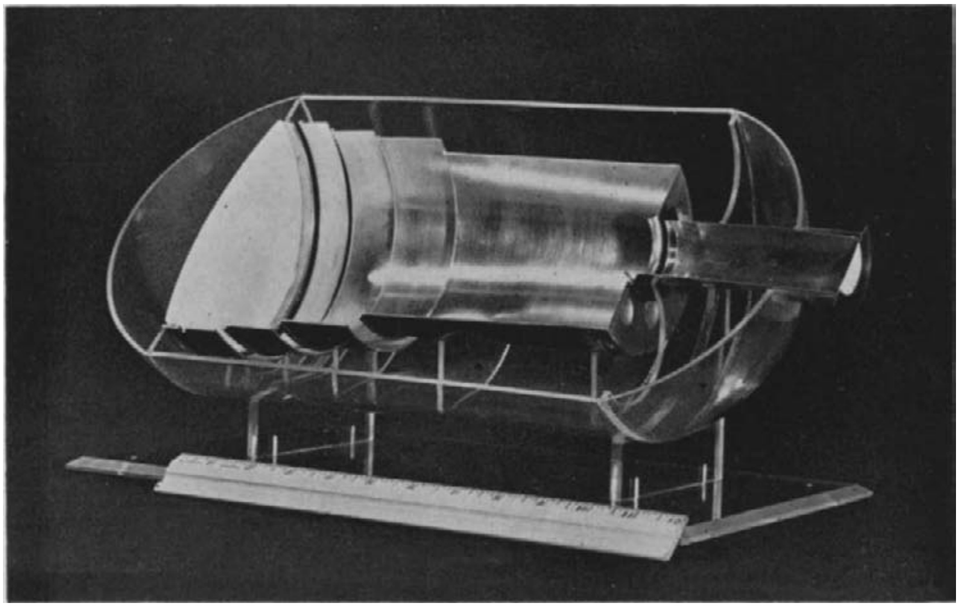

Fig. 3. Cut-away model of the large image tube.

A brightness gain of 25 times is thus introduced by this device. If we combine this with the gain of 20 times due to the electron acceleration process we would have an apparatus delivering a 500-fold brightness amplification.

Such an image amplifier is now being constructed at the Westinghouse Research Laboratories. A cut-away model of the tube is shown in Figure 3 and a diagram outlining its operation in Figure 4.

The envelope of the tube is essentially a glass cylinder 7 1/2 inches in diameter and 15 inches long. Magnetic focusing has been done away with in favor of electrostatic focusing. Each of the metal cylinders shown forms with its neighbor an electrostatic lens. The electric fields between these cylinders act on the electrons in a manner similar to the action of glass lenses on light. Essentially the system consists of one main lens of considerable strength and a series of weak correcting lenses. The fluorescent screen and photosurface are coated on the inside of the curved dish which is five inches in diameter. The electron lens system forms an image on the output phosphor layer which is inverted and reduced to one inch in diameter. This is viewed through the optical magnifier, which re-inverts the image and restores it to its original size. The various lens cylinders in the tube are supplied with suitable voltages from a power supply which delivers about 20 kv. at a negligible current. One of the lens voltages is adjustable to permit focusing.

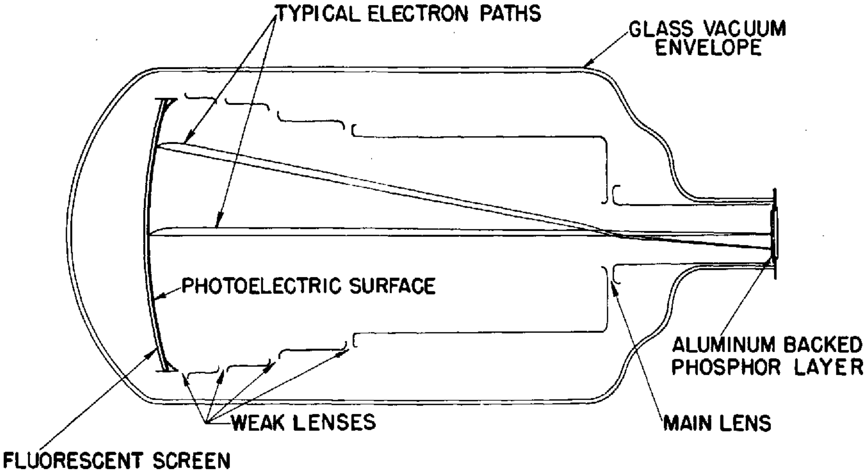

Fig. 4. Diagram of the large image tube. The mechanism of this tube is similar to that of the pilot model (Fig. 1) except that an inverted, reduced image is formed by a series of electrostatic cylinder lenses. The reduction in size produces another factor of 25 in brightness gain, bringing the total gain to 500. An optical magnifier (not shown) restores the size of the image to its original five-inch diameter with no loss of brightness.

A diameter of five inches was chosen for the field of view as a compromise among many factors. A larger diameter screen would have meant a proportional increase in the length of the tube, and would have added considerably to its bulkiness. Furthermore, it is increasingly difficult to maintain the resolving power of the electron optical system, and the requisite light-gathering power of the erecting ocular. Actually, the 12 × 16 screens now employed in fluoroscopy are seldom fully utilized over their entire area. For critical work the x-ray beam is invariably stopped down to include only the object of interest, as this improves the contrast by cutting down the scattered radiation. Moreover, the eye can examine critically only a rather small field of view at one time. For these reasons it was thought best to choose a screen large enough to cover a reasonable area but small enough to make the whole tube light and flexible, so that it might readily be moved over the region of interest. The electrostatic focusing system makes light weight construction relatively easy. The entire tube together with its housing, optical system, and protective lead shields, will be light enough to mount in place of the present fluoroscopic screen assembly on existing equipment. The power supply is relatively simple, for the current drain of the tube is only a fraction of a microampere, and a small power supply such as is used in some television receivers will suffice. Only two controls, for optical and electron focusing, are provided, and these will require only occasional readjustments.

With the advent of image amplification, many changes and improvements of fluoroscopic technic will be possible. All procedures now employed are primarily designed for maximum screen brightness attainable. This has often necessitated compromise solutions at the expense of image definition.

One important case in point is the wafer grid, which has proved so useful in radiography because of the increased contrast which it affords, yet which is very infrequently used in fluoroscopy because of the attending loss in brightness. This loss in brightness will no longer be a serious objection if we have at our disposal a brightness gain of the order of 500.

The amplifier will also open up the important field of stereofluoroscopy. Stereoscopic roentgenograms are widely used and play a most important part in diagnostic roentgenology but, in spite of many attempts, no successful stereofluoroscope has ever been built. The physical principles of such machines are sound, and impressive demonstrations have been made using metallic objects at relatively high brightness levels (4). However, with objects of low contrast, and at ordinary fluoroscopic brightness levels, the stereoscopic effect observed is very disappointing. The simple facts of the matter are that stereoscopic vision depends to a high degree on the perception of detail, and rod vision is not competent for this work. At 500 times the brightness, we will in most cases be well within the region of cone vision, and stereofluoroscopy will assume its rightful place as a standard technic of the roentgenologist.

As one of the most striking changes undoubtedly to come, we may anticipate a marked reduction in the time of examination. The increased brightness will permit acquisition of the desired information in a relatively short time. The long observations now necessary to make sure of the absence of certain diagnostic evidence will be in many cases cut short by the immediate appearance of that evidence. This reduction in time, besides being a saving in itself, will have a very salutary effect on both the patient and the fluoroscopist, for the exposure to direct and scattered x-rays will be similarly shortened. In addition, it might be desirable under some circumstances to relinquish a portion of the brightness gain in favor of reduced x-ray intensities at the skin of the patient. The x-ray kilovoltages and filters used may be modified somewhat, but in general the tendency will be to approach the conditions which produce at present the best roentgenograms.

The necessity for dark adaptation will be considerably reduced. It will still be desirable to dark adapt to some degree, but since under most conditions cone vision will be usable, and the cones in the fovea centralis are nearly fully dark-adapted in three to five minutes, the required time will be markedly shortened.

The apparatus described here is only the beginning of what may be a revolution in the field of radiology. There is no apparent reason why these brightness gains may not be doubled and redoubled many times. With the 500-fold increase in brightness, the image is well within the range of present day television pick-up tubes. This opens up a whole new series of possibilities; the radiologist may be at some distance from the patient, or even in another room, and images may be transmitted and duplicated at different points for observation by several persons. Whatever the fluoroscopes of the more distant future may be like, it appears certain that the new electronic technics will soon place in the hands of the radiologist vastly improved tools for clinical fluoroscopy.

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SUMARIO

Cómo Abrillantar la Imagen Fluoroscópica

Hace varios años el Dr. W. Edward Chamberlain indicó la conveniencia de encontrar algún medio de amplificar, o abrillantar, la imagen fluoroscópica. Tal cosa se ha conseguido, mediante la conversión del *quantum* (unidad elemental) de rayos X a una corriente de electrones, acelerando éstos a elevadas velocidades. En un aparato que se construye actualmente, la corriente de electrones se enfocará electrostáticamente en una capa fosforescente a fin de obtener una imagen reducida, cuya brillantez aumenta en proporción inversa al grado de reducción. Al observar dicha imagen con un amplificador óptico usual, vuelve de nuevo a su tamaño original sin perder su brillantez.

Se espera que la imagen, 500 veces más brillante, obtenible por este método permitirá efectuar exámenes en menos tiempo, disminuyendo el peligro, tanto para el paciente como para el radiólogo, de los rayos directos y esparcidos, y también acortando el período necesario para adaptarse a la obscuridad. Con este método quizás sea práctico emplear las técnicas de la rejilla tipo oblea, la estereofluoroscopia, y hasta tomar películas de las imágenes fluoroscópicas.

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