SCREEN INTENSIFICATION: A REVIEW OF PAST AND PRESENT RESEARCH WITH AN ANALYSIS OF FUTURE DEVELOPMENT*

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I. INTRODUCTION

SEVEN years ago at the annual meeting of the American Roentgen Ray Society, the first symposium on the subject of fluoroscopic screen intensification was presented. On this occasion, several investigators reported for the first time, work which indicated that the development of clinically practical screen intensifiers was not far away. History, of course, since 1948 has borne out the cautious optimism expressed at this early symposium. Commercially available screen intensifiers have become a reality, and although they have not yet been widely used, there is every reason to believe that they will be when improvements in design are forthcoming.

It is not known when the need for screen intensification in the field of diagnostic roentgenology was first recognized. Almost certainly, the early pioneers at the beginning of this century were frequently annoyed by the fact that their fluoroscopic screens yielded much less diagnostic information than their roentgenographic plates; many probably related this fact to the low brightness levels of the screens. At least, some of the early electronic research in this country was directed toward the development of increasing screen brightness. In the United States Patent Office, sketches, dated about 1915, are on file which show an electronic system whereby screen brightness can be increased. It is interesting, in this connection, that these sketches disclose a new all-electronic system of television which has since become the basis of present-day television. The proposed techniques did not have immediate application to radiology, since the science of electronics had not advanced sufficiently. However, they make it clear that, from a historical standpoint, considerable thought was given to increasing the brightness of the fluoroscopic screen at least forty years ago.

During the 1920's and 1930's, little progress was made in the devolopment of research programs on screen intensification. It is true that the manufacturers of fluorescent screens were continually improving the efficiency of their products by small increments. Also, when radiologists met in informal discussions, the subject of screen intensification was frequently considered. A perusal of my files recently revealed correspondence with Dr. Paul C. Hodges in the late 1930's on methods to brighten the fluoroscopic image. However, it was Chamberlain's monumental Carman Lecture[1] in 1941 which brought into focus finally the serious physiological disadvantages under which radiologists operate when performing conventional fluoroscopy, and the many benefits which would ensue if methods to brighten fluoroscopic screens by factors of several thousands of times could be designed.

Chamberlain demonstrated that roentgenograms made with fluoroscopic screens in contact with film exhibit much more detail than the same screens when used in fluoroscopy. A few years before, Hecht[3,4] had shown that the human eye, when viewing fields having a brightness approaching that encountered in fluoroscopy (10^{-4} to 10^{-2} millilamberts) had a visual acuity, or ability to perceive detail, of only a small fraction of that occurring under normal lighting conditions (10 to 100 millilamberts). Chamberlain, therefore, reasoned that the poor performance of the fluoroscope may be attributed to deficiencies of

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the human eye when operating at the low levels of illumination which exist during fluoroscopy rather than to any inherent imperfections in the fluoroscope itself and that this performance should be improved many times if the brightness of the screen were increased to levels at which the eye performs more satisfactorily. As a result of Chamberlain's discussion, interest in the subject of screen intensification was given an enormous impetus and experimental work was undertaken in a number of laboratories in this country and abroad soon after the end of World War II to develop practical screen intensifiers.

II. THEORY OF SCREEN INTENSIFICATION

Before these research developments are described, it may be well to review, briefly, the fundamental principles of fluoroscopic vision, for it is on these principles that the future of screen intensification seems so promising. At the outset, it may be said that, although the conclusions which may be drawn from the work of Chamberlain and Hecht are quite encouraging from the standpoint of the benefits to be derived from screen intensification, the premise that an improvement in fluoroscopic clarity will surely follow an increase in brightness of the fluoroscopic screen should not be wholly accepted until it is certain that the causes of the poor visual acuity which occurs at low levels of illumination will not also influence the performance of any man-made optical device which may be used to increase screen brightness. It is entirely possible that the limitations of the human eye are caused by factors which also limit all types of optical systems, physical as well as physiologic. If this is the case, the use of an intensifying device in conjunction with the fluoroscope will make little if any improvement in screen clarity.

It will be well to ask what are the factors which control the clarity of fluoroscopic vision. Over the years, there has accumulated a copious literature which indicates that these factors include the grain size of the fluoroscopic screen, the geometric unsharpness of the roentgen-ray beam, as well as the characteristics of the human eye. Although all of these factors impose limitations on the clarity with which fluoroscopic images are visualized, there is yet another factor which is even more fundamental.

The images appearing on a fluoroscopic screen are produced by the projection of a roentgen-ray beam through the anatomical structure which one wishes to visualize. Such a beam is composed of myriads of photons or roentgen-ray quanta. On passing through the anatomical structure, many, and sometimes most, of these photons are absorbed by the structure; some, however, pass through to emerge on the other side and thence to fall on the fluoroscopic screen. In the screen, these roentgen-ray photons are converted into light, whereupon they may be observed.

If all anatomical tissues absorbed roentgen-ray photons equally, the number of photons emerging to fall on the fluoroscopic screen would be uniform from one portion of the screen to another and hence the light generated by the screen would have no image pattern whatever. Fortunately, however, some tissues absorb more roentgen-ray photons than others, and hence the brightness of the fluoroscopic screen is not constant from one point to another but instead varies in accordance with the configurations of the anatomical structures through which the radiation has passed. In this way, the light emitted by the fluoroscopic screen bears an image pattern.

From this description of the manner by which fluoroscopic images are produced, it will be clear that the diagnostic information provided by a fluoroscopic image is carried from the patient to the screen by the myriads of roentgen-ray photons which comprise the roentgen-ray beam. Indeed, each photon which is transmitted from the patient to the screen carries a certain small amount of diagnostic information and it is the sum of all of the increments of information carried by these photons which controls the total quantity of diagnostic information provided by the screen at any instant. The amount of information provided by the screen can never be greater than that carried by the photons which impinge on it. The amount of information, of course, can be less, if such factors as grain size and geometric unsharpness do not permit efficient utilization of the information carried by the photons. The point that must be emphasized, however, is that the diagnostic information provided by a fluoroscopic screen can be no greater than the sum of all of the increments of information carried to the screen by the photons of the roentgen-ray beam. Since the quantity of diagnostic information provided by a screen is a measure of the screen's clarity, it is evident that fluoroscopic clarity is a function of the number of roentgen-ray photons falling on the screen during the fluoroscopic process.

Since each roentgen-ray photon may be assumed to have associated with it a certain amount of diagnostic information, it follows that when a roentgen-ray beam of high intensity is projected through a patient, the clarity of the fluoroscopic images will be considerably greater than when a beam of low intensity is used. In the first instance, there are a great many roentgen-ray photons carrying diagnostic information to the screen and hence the clarity of the resulting images is relatively good; in the second instance, the number of roentgen-ray photons is smaller and hence less diagnostic information is brought to the screen with resulting degradation of image quality.

From this discussion, it may be reasonably concluded that if one wishes to see more at fluoroscopy, one need only increase the milliamperage applied to the roentgen tube. Experience proves that such a conclusion is entirely valid. Indeed, if one operates a fluoroscope at 50 milliamperes instead of 5 milliamperes, the detail which can be perceived on the screen is considerably greater. Perhaps such an experiment proves better than in any other way the fact that grain size in the fluoroscopic screen is not a fundamental controlling factor affecting clarity of detail. If grain size were the controlling factor, the increase in milliamperage from 5 to 50 milliamperes would not have produced any change in visible detail whatever.

The question may now be asked as to what will happen to fluoroscopic clarity if one brightens the screen, not by increasing the milliamperage of the roentgen tube, but by introducing into the fluoroscopic process a screen intensifier of one sort or another. On the basis of the preceding discussion, it would appear that no increase in clarity should occur. Even if the fluoroscopic screen is made brighter by a screen intensifier, the fact that the milliamperage on the roentgen tube, and hence, the number of roentgen-ray photons which take part in the fluoroscopic process are not increased, indicates that no more diagnostic information is carried from the patient to the screen and hence no improvement in screen clarity can be expected. The only circumstance under which this reasoning will not be valid is one which occurs if the eye under the conventional fluoroscopic process does not utilize 100 per cent of the information transmitted from the patient to the screen by the roentgen-ray beam's photons. Under such a circumstance, it might be possible by means of a screen intensifier to improve conditions in such a way that greater utilization of photon information could be effected.

On the basis of measurements made by Sturm and Morgan[11] in a study of optical physiology as it relates to fluoroscopy, it appears that the human eye, during conventional fluoroscopy, utilizes the diagnostic information of only a small fraction (about 1 to 5 per cent) of the roentgen-ray photons received at the screen. Hence, if it were possible, by the introduction of a screen intensifier, to improve the efficient utilization of these photons, a considerable improvement in the diagnostic clarity of fluoroscopy could be developed. For example, an improvement in the efficiency of the fluoroscopic process from 2 per cent to 100 per cent would effect an improvement in screen detail equivalent to that produced by an increase in the roentgen tube current from 5 milliamperes to 250 milliamperes. We know by experience that the improvement in detail with such a change in milliamperage is indeed very great. It, therefore, is evident that the introduction of a screen intensification system which improves the efficiency of fluoroscopic vision will also improve fluoroscopy very materially.

It must be emphasized that the introduction of a screen intensifier into the fluoroscopic process will, under no conditon, improve the clarity of fluoroscopic vision if it only increases the brightness of the fluoroscopic screen without increasing the efficiency of roentgen-ray photon utilization over that which occurs at conventional fluoroscopy. Indeed, if at conventional fluoroscopy, the eye utilized 100 per cent of the information carried from the patient to the screen by roentgen-ray photons, no improvement in fluoroscopic clarity could be expected under any circumstances. It is only the fact that the eye utilizes a small fraction of the information carried by the roentgen beam that screen intensification holds promise of success. Fortunately, the evidence from studies in optical physiology[10,11] indicates that screen intensification has a considerable opportunity to improve fluoroscopic efficiency and we can confidently expect fluoroscopy with screen intensifiers to yield a degree of clarity which approaches and in some instances exceeds that of roentgenographic film.

III. DEVELOPMENTAL RESEARCH

Since the end of World War II, considerable progress has been made toward the development of practical instruments whereby the luminance of fluoroscopic screens may be increased or intensified. The instruments which have been developed fall into three broad categories: (a) instruments which employ simple electron optical systems;[2,9] (b) instruments which use storage-type televison circuitry;[7] and (c) instruments which are based upon the flying-spot principle of televison.[6]

(*a*) *Electron optical intensifiers.* Screen intensifiers of the simple electron optical type are shown schematically in Figure 1 and 2. The first is the instrument currently being manufactured by the Westinghouse Electric Company in this country and the second is the intensifier being produced by the Philips Company of Holland. Each of these devices consists of an evacuated tubular glass envelope in which are located a more or less conventional fluorescent screen at one end of the tube and an aluminum-backed phosphor layer at the other. The inner surface of the fluorescent screen is covered with a thin photoelectric layer and, between the screen and phosphor, are placed a number of cylindrical electrodes which serve as electron lenses when suitable electric potentials are applied to the photoelectric layer, the electrodes and the phosphor. The intensifier operates in the following manner: Radiation from a conventional roentgen tube is projected through the patient and is allowed to impinge on the instrument's fluorescent screen. In response to the light generated

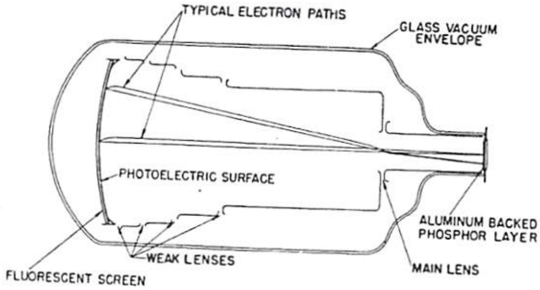

Fig. 1. Schematic diagram of Westinghouse screen intensifier. (Reproduced by courtesy of Westinghouse Electric Corp.)

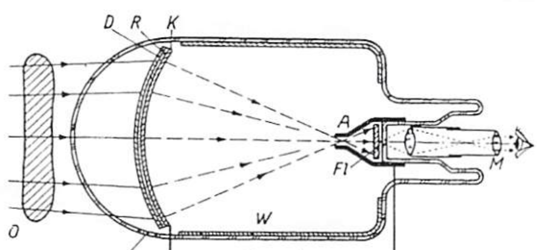

Fig. 2. Schematic diagram of Philips screen intensifier. (Reproduced from *Acta Radiologica.*)

by the screen, the photoelectric layer emits electrons having a spatial distribution proportional to the brightness of the screen. That is, the fluorescent screen converts the roentgen-ray image into a light image whereupon the photoelectric layer creates a corresponding electron image. The electrons from the photoelectric layer are accelerated down the length of the tube under the influence of the electric potentials applied to the cylindrical electrodes and fall on the phosphor at the tube's distant end. The impingement of the electrons on this phosphor produces a visible image which duplicates the pattern of that appearing on the roentgen-ray fluorescent screen. However, due to the acceleration of the electrons within the tube, the brightness of the phosphor is many times greater than that of the screen. The brightness is further increased by the fact that the size of the phosphor is small compared to that of the fluorescent screen. The observer views the intensified image appearing on the phosphor by means of a telescopic eye piece or other optical system to bring the size of the image back to normal perspective.

The advantages of electron optical intensifiers are their great simplicity, their relatively low cost, and, above all, their theoretical ability to improve the efficiency of the fluoroscopic process from the standpoint of the observer's ability to see to a level closely approaching 100 per cent. The quality of image rendition in these tubes is therefore excellent, particularly in examinations of the chest and extremities. Their disadvantages include a somewhat limited increase in brightness over conventional screens (500 to 1,500 times), a small field size (5 inches in diameter), a low inherent contrast (about the same as that of conventional fluoroscopes as opposed to the much higher contrast of roentgenographic films) and a tendency to undergo deterioration in image quality during the examination of thick structures due to fogging of the viewing phosphor by spurious electron emission from within the tube. Another disadvantage experienced by some workers is one's need to view the intensifier through an optical device; freedom of motion for the observer is therefore rather confined. Although these disadvantages are sometimes bothersome, it is the general feeling of those who have worked extensively with electron optical intensifiers that their advantages far outweigh their defects and that these instruments constitute a marked step forward in the solution of the screen intensifier problem.

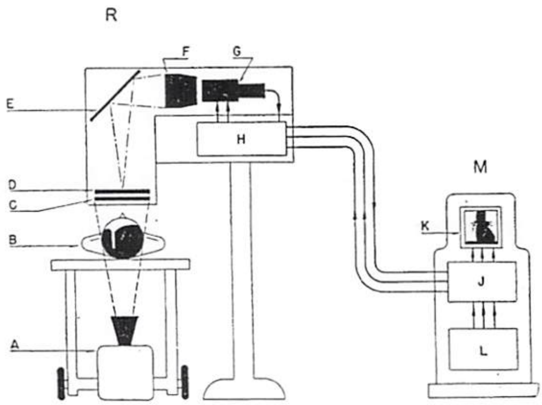

Fig. 3. Schematic diagram of television-type screen intensifier. (*A*) Fluoroscopic roentgen-ray generator; (*B*) Patient under examination; (*C*) Wafer grid; (*D*) Fluoroscopic screen; (*E*) Plane mirror; (*F*) High speed lens; (*G*) Image orthicon; (*H*) Preamplifier; (*J*) Final amplifier; (*K*) Viewing screen (cathode-ray tube or kinescope); (*L*) Pulse former for generating electrical pulses to sweep the electron beams of the image orthicon and kinescope synchronously with one another.

(*b*) *Storage-type television intensifiers.* The details of a typical intensifier using storage-tube television circuitry is shown schematically in Figure 3. This instrument, like the intensifiers of the electron optical type, employs a conventional roentgen tube, the radiation of which, after projection through the patient under examination, falls on a conventional fluoroscopic screen. The light from this screen is focused by a lens system on the sensitive surface of an image orthicon (the photosensitive tube employed in many television cameras in this country). In response to the light falling on its sensitive surface, the image orthicon generates an electrical signal which, after amplification, is impressed on the control grid of a cathode-ray tube whose electron beam is swept systematically over the surface of the tube synchronously with the electron beam within the image orthicon. Hence, there appears on the surface of the cathode-ray tube a fluoroscopic image of the patient. Due to the amplification which takes place within the instrument, the brightness of the fluoroscopic image is many times that normally seen on conventional fluoroscopic screens.

The advantages of the storage-type television intensifiers are the relatively large gain in screen brightness (up to 50,000 times the brightness of conventional screens), a screen size that can be tailored to almost any need (sizes as large as 3 feet square have been used for some industrial applications), high and controllable image contrast (equal to and exceeding roentgenographic film), the absence of special optical devices for viewing the intensified image, and the independence of the viewing unit's location relative to that of the radiation detector unit. The disadvantages include relatively great complexity of design, comparatively high cost and an efficiency in utilization of roentgen-ray photons of less than 100 per cent. Complexity of design and cost have limited the application of this type of intensifier to some extent. However, when these factors are unimportant, the storage-type television intensifier has proved itself quite useful in a number of problems which cannot be solved either by conventional fluoroscopy or by electron optical intensifiers.

(*c*) *Flying-spot television intensifiers.* Very little success has been experienced by workers who have been exploring the flying-spot type of television intensifier. The extremely low efficiency with which roentgen-ray power is utilized by this device makes it seem unlikely that it will have practical application in the foreseeable future.

IV. APPLICATIONS

Since screen intensifiers have been available for only a short time, their application has, of course, been limited. A number of radiologists have been using intensifiers of the electron optical type in conventional fluoroscopy and most are enthusiastic about their performance.

Probably the area where screen intensification has enjoyed the greatest activity during the past two or three years is the field of cinefluorography. Until the advent of screen intensification, cinefluorography was extremely limited as a practical procedure due to the enormous radiation dosages to which patients were exposed unless very short sequences were performed. With screen intensification, however, this difficulty has been overcome so that motion pictures of long roentgenologic sequences can be undertaken with radiation exposure to the patient of no more than that employed during conventional fluoroscopy. Also, since the screen intensification process is inherently efficient in its utilization of available roentgen-ray energy, the quality of cinefluorograms made with screen intensifiers is usually equal to or greater than that of films made with older, less efficient techniques, even though the latter uses much more radiation. At the present time, there is much interest in cinefluorography in this country and abroad and it is expected that the technique will be widely used in the study of many physiological problems. Intensifiers of both the electron optical and television types are being used in this application and both are providing good service.

The ability of one to separate the viewing unit from the radiation detector to almost any desired distance in intensifiers of the television type has made these devices unusually suitable to a number of applications. In industrial radiography, where for protective reasons it is desirable to place the observer remote from the radiation source, these instruments have proved quite useful. In time, this feature may well prove worthwhile in medical fluoroscopy. For example, in radiation therapy, television-type intensifiers have been used successfully as a beam localizing fluoroscope[8] with the radiotherapist observing the

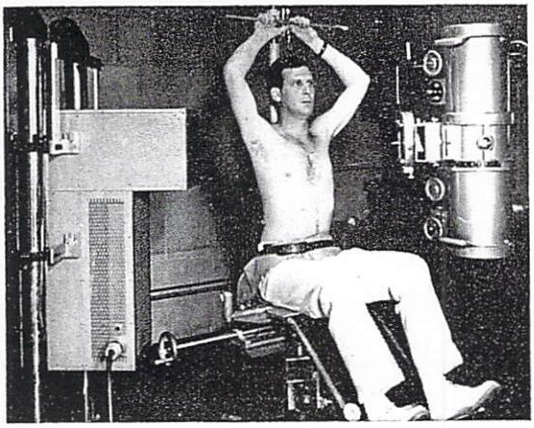

Fig. 4. Application of screen intensification to roentgen therapy. Apparatus permits precise localization of radiation to desired region of treatment.

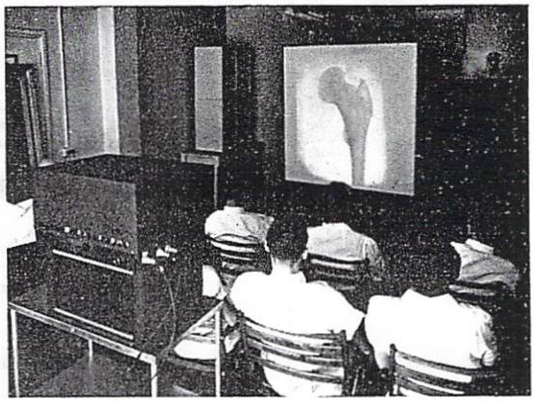

Fig. 5. Projection kinescope for demonstration of fluoroscopy to large audiences.

screen in safety in the control room outside of the therapy area. Such an application is shown in Figure 4.

Screen intensifiers of the television type are also of considerable usefulness in teaching. With this instrument, it is possible to attach additional viewing units and television projectors by which fluoroscopy can be presented clearly to large groups of students and physicians (Fig. 5). This application is one which seems likely to be increasingly adopted as time goes on.

FUTURE DEVELOPMENTS

With screen intensification just beginning to become a significant force in the field of radiology, the question arises as to what may be expected in the future. In the field of instrumentation, work is in progress in a number of laboratories which indicates substantial improvements in equipment will be forthcoming in the next few years. Much effort is being directed toward the development of electron optical intensifiers with larger field coverage (10 inches or more). Research is also going on in at least two laboratories in this country on the development of television-type detector tubes which are directly sensitive to roentgen rays as opposed to present day tubes which operate from light from an external fluorescent screen. When these roentgen-ray sensitive tubes are available, intensifiers of the television type will be greatly reduced in complexity, and their efficiency should approach the 100 per cent level characteristic of intensifiers of the electron optical type.

Current research may also produce types of intensifiers which are quite different in design than those now available. The electroluminescence properties of some phosphors are being studied, particularly at the General Electric Company, and it seems probable that relatively simple screens no more bulky than conventional screens and providing brightness gains of 5 to 25 times may be possible to design. Electroluminescence[5] is the property of some fluorescent materials to increase in brightness when placed in an alternating electric field; such a field can be produced by two sheets of conducting glass placed on either side of the fluorescent screen and connected to a suitable potential a.c. source.

From the foregoing, it is clear that much is to be expected from research during the next few years in the development of new and improved intensification devices. These developments will probably be evolutionary rather than revolutionary, and they may be expected to extend the usefulness of present day intensifiers rather than replace them.

If the future of instrumentation in the field of screen intensification appears to be one of expanding growth, such growth will perhaps be dwarfed by that which should take place in the medical and industrial applications of these devices. The application of screen intensification techniques to the study of many physiological problems can be confidently expected. Stauffer in Philadelphia and Miller in San Francisco as well as several others are already hard at work in this field. In radiation therapy, in radiologic teaching and in industrial radiography, considerable growth in screen intensification techniques will almost certainly take place. Of course, it may also be confidently expected that screen intensifiers of one type or another will supplant conventional fluoroscopic screens within the next decade or two.

Like any research development which promises to have an enormous influence on a given branch of science, screen intensification, its techniques and the knowledge gained therefrom are likely to prove valuable in a variety of corollary scientific areas. For example, the light-sensitive section of a television-type intensifier has been used recently at the Lowell Astronomical Observatory at Flagstaff to yield photographs of the planets of considerably greater detail than those heretofore taken under similar conditions. The same apparatus has also been used to permit the photography of night scenes, illuminated only with starlight, with conventional film and lenses at the unusually short exposure time of 0.1 second. Electronic research in the extremely low ranges of light intensity which has been needed to solve the problems of screen intensification seems likely to prove equally useful in many scientific, industrial and military applications beyond the boundaries of radiology.

Such, then, is screen intensification in 1955, as seen from the limited perspective of one observer. It seems unlikely that the views expressed here will have any long-standing value, but if they do, it will probably be to illustrate how incompletely one man can grasp the significance of developments going on about him in an enormously expanding science.

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REFERENCES

1. Chamberlain, W. E. Fluoroscopes and fluoroscopy. *Radiology*, 1942, *38*, 383–413.
2. Coltman, J. W. Fluoroscopic image brightening by electronic means. *Radiology*, 1948, *51*, 359–366.
3. Hecht, S. Relation between visual acuity and illumination. *J. General Physiol.*, 1928, *11*, 255–281.
4. Hecht, S. Quantum relations of vision. *J. Optic. Soc. America*, 1942, *32*, 42–49.
5. Low, W., Steinberger, J. T., and Braun, E. A. Effect of alternating electric fields on excitation of strontium sulfide phosphor. *J. Optic. Soc. America*, 1954, *44*, 504–505.
6. Moon, R. J. Amplifying and intensifying fluoroscopic image by means of scanning x-ray tube. *Science*, 1950, *112*, 389–395.
7. Morgan, R. H., and Sturm, R. E. The Johns Hopkins fluoroscopic screen intensifier, *Radiology*, 1951, *57*, 556–560.
8. Morgan, R. H., Sturm. R. E., Miller, L. S., and Torrance, D. J. Remote fluoroscopic control of radiation therapy by screen intensification. Am. J. Roentgenol., Rad. Therapy & Nuclear Med., 1953, *70*, 705–708.
9. Oosterkamp, W. J. Image intensifier tubes. *Acta radiol.*, 1954, Suppl. 116, 497–502.
10. Rose, A. Sensitivity performance of human eye on absolute scale. *J. Optic. Soc. America*, 1948, *38*, 196–208.
11. Sturm, R. E., and Morgan, R. H. Screen intensification systems and their limitations. Am. J. Roentgenol. & Rad. Therapy, 1949, *62*, 617–634.