X-Ray Image Intensifiers: Applications and Current Limitations

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X-ray image intensifiers: applications and current limitations

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Early intensifiers having small fields of view and poor contrast were so difficult to use with normal patient tables that specialized use was the rule, and routine work unusual, though rewarding in patient dosage and detail rendition, when aerial images were used. Deposited amorphous screens suffered traumatic voids, severe halation and short lifetimes.

Closed-circuit television presentation led to widespread acceptance of intensifiers for gastro-intestinal work and provided variable contrast for cardiac and renal examinations, but quantum and shot noise were suppressed by increased radiation dosage. Lag prevented close study of moving organs.

Caesium iodide input screens provide physical stability, reduced halation, high contrast, improved definition, short lag, with increased quantum absorption efficiency at 'diagnostic energies'.

Reduced closed-circuit television gain and noise improve low contrast soft tissue differentiation, particularly with relative motion; lung metastases are detected before radiographs confirm, and small contrast-filled vessels are sharply defined for cineradiography.

Current developments include compact intensifiers, whose field of view accepts cardiopulmonary images or includes the liver, spleen and both kidneys, or the kidneys and a considerable length of both ureters, for functional or vascular studies.

Few devices can have led to such a marked change in ambience for the patient, with a clearer view of his internal structure and dynamics for the examining doctor, than the image intensifier. However, the reception that they received in their earliest days can hardly have been encouraging to the engineer, and the present excellence of intensifiers is best appreciated by their history.

There have been two main methods of studying the varying intensities of X-rays which remain after differential absorption of a sensibly homogeneous beam by some part of the human body. One was use of the X-ray film, which recorded a two-dimensional image during the short period of an X-ray exposure. The second method was to observe a moving shadowgraph visually on a fluorescent screen, which even after much technical improvement produced a luminance of only 10^{-5} to 10^{-2} cd/m^2, at which level lengthy dark adaptation was mandatory.

Chamberlain (1942) commented that there was remarkably little difference between 1941 models of commercially available fluoroscopes and one sold in 1912. He also stated that a brightness gain of at least 1000 times would be needed to give reasonable cone vision. Electronic image brightening proved to be the answer, and there are several approaches of medical interest: (1) the solid-state amplifier, which has been tried but found wanting (Fowler 1960); (2) the channel multiplier, not yet available to the radiologist; (3) the image Isocon brightener of Marconi; (4) the light amplifier of Cinelix and others, which produced one of the largest fields of view for the radiologist until quite recently; (5) what has come to be known as the X-ray image intensifier, the subject of this paper. The first commercial form of this instrument came into my hands in 1953; basically its internal structure is unchanged, and well known to engineers in this field.

The output screen image is small, of the order of 25 mm diameter, and so far as the medical user is concerned, the performance of an intensifier is inseparable from the means of viewing this image. These range from wide-aperture lens and mirror systems to fibre optic-coupled television camera tubes, with a multiplicity of permutations for viewing and recording, each of which has its own problems. For example, the wealth of information available in the output screen image can be reduced significantly by passage through closed-circuit television, or entirely lost in its periphery, owing to vignetting in a lens system.

The limited diameter of the viewing area of the original 'five inch' intensifier was not necessarily a disadvantage. The most pressing need has been for increased quantum efficiency of the conversion of X-ray photons to visible light in the primary screen. Without this, a large gain results in severe quantum mottle, particularly in fluorographs taken through the intensifier. Although one could observe directly a stationary well defined image on the output screen by using a microscope and normal visual integration, as soon as one attempted to take photographs, particularly in rapid sequence as in cine radiography, the dose to the input screen of the intensifier had to be increased to provide a picture of acceptable quality.

The early primary screens were of deposited powder and had to be treated with care, since they were amorphous, with poor adhesion and liable to detachment with consequent voids in the image. The better adhesion of the current evaporated screen means that one can park the intensifier in a position providing maximum safety from impact; many are suspended from ceilings, as are X-ray tubes, television monitors and even control panels. The shield of the intensifier tube should be strong enough to resist deformity from any but serious accidental impact; the evacuated vessel itself needs to have considerable physical strength, and the electrodes need to be firmly fixed relative to each other and the container to avoid shifts in the image. About 1960, in order to avoid some of these problems, the author's intensifier was moved in a fixed horizontal plane, and the patient was moved in front of the primary screen by a supporting stand.

The most efficient manner in which to view the output screen was through a binocular microscope.

Image presentation is important; a recent editorial comments that due to the clustering of cones at the fovea there is limited area in which details can be appreciated at a glance. This area is said to have a diameter of about 18 cm at 50 cm viewing distance (Loop 1977), and lends support to my contention that larger areas are misused when applied to fluoroscopy.

The initially small area available for recording was rapidly reduced to an annulus in the short lifetime of the early tubes. If one was dedicated to a failing intensifier, it was much better to use it solely as an aiming device for a cassette film taken proximal to the intensifier, than to attempt fluorography through it.

The demand for a larger area for fluoroscopy led to the first 23 cm intensifier. Brightness gain and detail over the area of the picture were improved, but deteriorated rapidly, and to get maximum value the instrument had to be used intensively during its relatively short life. One further problem was the pincushion effect. This had always been present, but with a 23 cm field the shutter edges should be more often in the field of view than with the 13 cm field and appeared curved. This distortion affected all parts of the image to some degree, and therefore an organ whose edge was near that of the intensifier field was not necessarily of the displayed shape. For fluoroscopic purposes this did not matter, since one could bring the object to the centre of the field where the distortion was less, but in a fluorographic film the effect was disturbing. If fluorography were to displace direct radiography, this distortion would be important in all procedures in which measuring has to be carried out, as in orthopaedics.

Although the use of an intensifier with optical viewing can significantly reduce the radiation dosage both to the patient and the operator, the use of television viewing with the same intensifier will increase the dose rate to the same level, or even a higher level than was current before the coming of intensifiers. The consequences are significant in the case of gastro-intestinal examinations. Most radiologists will have carried out some tens of thousands of these in a working lifetime, and the demand continues unabated in spite of the advent of endoscopy. Resolution and contrast are already sufficient in the image, as viewed live, to make a firm diagnosis or to be convinced of normality in most instances. Eminent members of my profession are beginning to question the value of television for those procedures carried out most commonly: those of the gastro-intestinal tract. A wide-angle mirror viewer is adequate when a normal tilting patient table or couch, controlled from the vicinity of the intensifier, is used.

A writer who has used the most advanced equipment over a considerable period has recently commented that, since an additional image relaying unit has an unfavourable effect on image quality for fluoroscopy, we should do well to consider the alternative of a mirror viewer with a large exit pupil (Feddema 1977). It could also be said that if the main uses of fluoroscopy are study of movement, positioning, and timing of events, there is no need to display details smaller than those detectable with existing closed circuit television. Certainly there is some doubt of the value of so-called high definition television (Samuel & Philip 1977). The manufacturers do not agree and argue that a television viewing system is beneficial to the radiologist, because the contrast of the television picture is higher than that of the original intensifier output picture (Haendle & Pfeiler 1978).

The use of high-performance closed-circuit television with an intensifier has been described as 'quite subtle' by A. R. Chrispin (personal communication), in that the movement of low-contrast details relative to the bone of ribs, in lung partially drained of blood by positioning, makes them more readily detectable than in conventional films of good quality. For such a system to work, loss of information in the intensifier system must be held to a low level.

The use of television for location or positioning for radiography is more problematical. The increase in integrated dosage has been said to be insignificant. Certainly this will be so if the viewed area is small, but with an area of 35 cm diameter available for radiography, it is tempting to use that same area for fluoroscopy. This will bring the edge of the incident beam close to the surface of the patient, and scatter to the operator will be considerably increased. A desirable development would be an automatic beam-limiting diaphragm which would reduce the field of view to that sufficient for centring correctly, and which would open to the full area determined by the radiographer before the exposure. From the earliest days the use of a circular diaphragm has been desirable, since otherwise four areas at the corners, invisible to the fluoroscopy observer, will be irradiated to no purpose.

Modulation of the electrical signal in television allows contrast enhancement, harmonization and edge enhancement, which may facilitate observation, but cannot increase the information received from the intensifier. Resolution in the centre of 23 and 25 cm diameter intensifiers already in clinical use is better than 20 line pairs per centimetre. Absorption of X-radiation by the input screen has been increased to as much as 65 %, and halation has been reduced by the use of caesium iodide crystals. During fluoroscopy it is possible to see variations in contrast of about 4%, provided the input dose is not too small to visualize all of the information. In order to obtain a reasonably grain free image, a minimum of 50 μR s^{-1} (12.9 nC kg^{-1} s^{-1}) is required at the input phosphor.

The limiting resolution of the output screen is very high: over 100 line pairs per centimetre, but halation here remains a problem, most recently being tackled by fibre optics.

In order to utilize as much as possible of the available light from an intensifier for photography, it has been usual to rotate a mirror to transfer light to a recording camera. Inertia plus the need to make an exposure with the mirror at rest demands a pause, possibly of several seconds, between viewing, exposure and viewing once more. Transient events are readily lost, and it has been usual to make rapid serial exposures before and during a predicted event, in order to be certain to capture this in at least one picture. This has increased the total X-ray dose per examination; it may also interrupt and prolong the examination, to allow scrutiny of films after processing. The facility to photograph the television image, without interruption of fluoroscopy and almost instantaneously, would be an advantage. The Marconi image brightener provided this facility many years ago, and pictorial quality was in the opinion of some sufficient for a record incidental to diagnostic fluoroscopy. What is now offered is the same facility of film exposure during uninterrupted fluoroscopy, from a high-quality intensifier with direct fibre optic coupling to the television camera tube.

A fibre optic plate in the output screen of the intensifier can both reduce halation and can also be shaped to reduce residual geometric distortion. It eliminates the moving mirror, but leaves the television camera system as the only means of recording the image photographically. In this situation high-definition television not only has a place but is highly desirable; for video fluoroscopy to be successful the bandwidth of the system should make it possible to record in excess of 20 line pairs per centimetre.

One manufacturer claims that this system permits X-ray television images to be obtained which 'in particular cases are of the same quality as direct radiography'. The author has no experience of this particular system.

Since the photographed monitor can be remote from the patient, and can also provide a very bright picture, the film can be any convenient size for viewing. However, when a camera is mounted on an intensifier, via a light distributor with suitable optics, the whole instrument can be bulky, and there may also be distortion or restriction of the area covered by the photographic image.

Successively 16, 35, 70, 100 and 105 mm wide film has been offered for fluorography, and miracles of engineering have been achieved in providing compact cameras which are also convenient to use. The full area of the input field is not always available in the photographic image; one has the choice of a circular intensifier enclosed in a larger square frame, the common format in the case of 70 and 100 mm film, or of a circular image within the oblong frame of 16 or 35 mm film, or of a partial intensifier field occupying a greater part of the 16 or 35 mm frame.

Cinefluorography assumes considerable importance in the recording of rapidly repetitive or transient phenomena. Cardiac studies are an obvious example, since valves are in motion, cavities are changing shape, and muscular walls are moving with variable degree of velocity (of the order of 10 cm/s), as also are the vessels in these walls, and one cannot stop the motion.

The X-ray generator is required to produce short repetitive exposures, when the recording film is at rest, to save radiation dosage and avoid blurring. The image intensifier must be capable of responding fully to short pulses of intense radiation, with as little halation as possible, and minimum lag.

For fluorography the 100 mm square film has proved very satisfactory since (1) it provides an image which can be examined by the naked eye, without enlargement, containing most of the useful information except at the periphery; (2) it saves filing space; (3) it saves material cost, the emulsion being on one side only (full-sized X-ray film is coated on both sides); (4) radiation dosage saving is the most significant advantage of fluorography.

Several workers have recorded dosage savings of 5–10 times (Berridge 1975; Schuster & Heinrich 1974; Ramtenburg 1975). Earlier workers (Wohl & Koehler 1965) found that the saving depended on radiographic kilovoltage, which has been my own experience, the saving increasing as the energizing kilovoltage is decreased within the diagnostic range. Before the advent of rare-earth intensifying screens (and matched films) for full-sized radiography, the author found that in the case of the closest approach between the two systems, producing films of similar diagnostic value, there was still an improvement of three times in fluorography. The manufacturers of rare-earth screens claim that radiographic speed achievable exceeds that of intensifier fluorography. My experience is that this is so only if quality is sacrificed. If the quality is similar, the intensifier image is obtained for a smaller radiation dose.

The relatively low dose for fluorography can also be inferred from other evidence. The short life of X-ray tubes used in conjunction with fluoroscopy units was until recently a by-word. The reason was the number of large film exposures made in quick succession, leading to overheating, crazing of the anode surface, and even disintegration of the anode disk. The coming of intensifiers did not change this situation, since the X-ray tube input during fluoroscopy is a few hundred watts only. Since the advent of fluorography and the consequent reduction in heat input resulting from smaller exposures, tubes in daily use by the author have been lasting up to 5 years, as opposed to about 1 year previously.

The elimination of large film or cassettes has meant that it is possible to reduce the mass and bring the input screen closer to the patient, with improved geometry and better use of the film format available on the 100 mm camera. Future developments should leave the intensifier short enough to maintain an under-table position for radiography.

Comments on the influence of X-ray tube position relative to the examination table, on scattered radiation close to the operator (Herstel 1965; Jacobson 1971), can be discounted in a purely radiographic intensifier situation, even if positioning by fluoroscopy is proposed, since in both cases the radiographer could be protected by a screen at his or her control point.

One writer has recently commented on the problems of recording three-dimensional anatomy on two-dimensional films (Keates 1978). Two pictures taken at right angles to each other are the time-honoured method. More recently, fluorographs have been taken through intensifiers of 25 cm input field diameter, which is not large enough to accommodate all desirable detail, particularly if this is not available right up to the periphery. Intermediate-angled views are desirable, since internal structures lie at all angles to the external surface of the body.

If the patient is under anaesthetic, uncooperative for other reasons, or coupled to external equipment via tubes or cables, it may be undesirable to rotate or to tilt him through large angles. It is then better to hold him in one position and to move the intensifier and X-ray source in relation to him. Machines which provide such complex movements are rewarding to use with a modern intensifier. For example, cranio-caudal angulation of the X-ray beam is useful in routine examinations of the sigmoid colon and of the stomach and duodenum (Persyn 1976), and in the study of congenital heart disease (Partridge 1978). Large changes in tissue opacity are involved in the changing X-ray beam length through the body, and input dose rate to the intensifier has to be varied to maintain picture quality, preferably by automatic means.

The breakthrough for photographic intensifiers could arise from the very advanced technology that has been incorporated in a new instrument with an input field diameter of 35 cm.

The evacuated container is all metal, apart from the output optical section. Input diameter can be 15, 25 or 35 cm. In the 25 cm field, geometrical distortion is wholly eliminated by a shaped fibre-optic plate, and is barely detectable when one of the other input diameters is used. The same fibre-optic plate virtually eliminates halation arising from the output screen (Kuhl 1975), but the most remarkable features of this instrument are concerned with resolution and its uniformity in the field of view, coupled with a compact physical form.

The external diameter of its protective shield is less than 46 cm; its overall length, including television and fluorographic camera, is just over 66 cm, whereas that of the 23 cm field unit currently used by the author is 1 cm longer.

Resolution is better than 40 line pairs per centimetre over the entire 35 cm field of view; peripheral loss of detail has been eliminated. This field comfortably accommodates the picture of an enlarged heart, or of both kidneys and a considerable length of both ureters.

Fluorographs of 100 mm made with the 35 cm field during arteriography have already shown a lumen of less than 1 mm diameter, right out to the periphery of the field of view.

Even better resolution is available from the switched fields of this intensifier, in excess of 60 line pairs per centimetre for the 15 cm field. This resolution is very similar to that of the best X-ray film, with due regard to patient X-ray dose and an automatic processor working at the peak of its performance.

A resolution of 60 line pairs per centimetre does not represent the limit that can be achieved, if very small fields of view are sufficient. An intensifier with an input diameter of 21 mm using an external caesium iodide screen and fibre-optic coupling to a plumbicon camera tube has defined vessels of about 30 μm lumen diameter during angiography in a dog. A similar light amplifier system with an 80 mm diameter input screen has been reported to provide better contrast than any image intensifier up to the end of 1975 (Davis & Glascock 1977).

Limited uses for intensifiers have been found outside the medical X-ray department, but sales have been few in the industrial field.

The development of channel intensifiers for industrial use is of interest to the radiologist (Chalmeton 1977), since with a suitable input screen of about 25 cm diameter he could be provided with a much thinner device than an image intensifier for routine study of movement. It could be mounted, moved, and viewed in the immediate vicinity of the patient.

As the use of ultrasonic methods of diagnosis becomes more precise, the justification for the use of ionizing radiation for medical diagnosis will come increasingly under criticism. The author believes that its continued use will depend on the superior quality of X-ray images, coupled with convincing efforts by both engineers and user to reduce radiographic X-ray dosage. For this reason, the future use of image intensifiers may be increasingly for fluorography.

SUMMARY

Requirements of image intensifier itself

Essential

(1) Significantly better radiation dosage performance for radiography than any other system of comparable image quality.

(2) An input field size large enough for most routine radiography.

(3) High absorption of incident radiation.

(4) Large light output with good contrast.

(5) Unobtrusive quantum noise.

(6) Resolution good for both fixed and moving images, over the whole viewing area.

Desirable

(1) The image intensifier shield and necessary attachments should have adequate mechanical strength, but should not be inconveniently bulky and heavy.

(2) Field sizes should be switchable, even in the largest intensifier, to allow full use of the film area.

(3) Long working life, commensurate with that of the associated hardware, i.e. 10–12 years.

Requirements of associated apparatus

(1) Reliability of closed circuit television and mechanical cameras.

(2) Stability, serviceability, and reproducibility of systems.

(3) Maintenance of specifications.

(4) Automatic X-ray beam diaphragms.

Note added in proof (28 *February* 1979): Between the dates of the presentation of this paper and its going to press, a channel multiplier has become available for medical fluoroscopy.

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