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# The Application and Limitation of the Use of X-Rays in Medical Diagnosis

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# The application and limitation of the use of X-rays in medical diagnosis

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X-rays in medical diagnosis are normally used to obtain a visual image of the subject radiographed. The image results from the differential attenuation of the radiation which depends on the thickness, density and configuration of the organ irradiated and on the proportion and nature of the different chemical elements present. The nature of biological material is such that the contrast differentiation between organs or parts of an organ is frequently poor and despite methods to increase the contrast this remains one of the principal limitations. Other limitations are similar in many respects to those found when using X-rays for non-destructive testing but additional limitations are imposed since when living subjects are examined, movement of the subject can seldom be eliminated and, because radiation may be harmful, the dose must always be kept as low as reasonably practical.

Further constraints are imposed by the high cost of some equipment and the shortage of qualified manpower to operate the equipment and interpret the findings. The number and type of examinations carried out may have to be limited in some very sick patients because they reach their limits of endurance. Practically every procedure therefore has to be a compromise between the advantages and the limitations imposed.

## Introduction

X-rays are used in medical diagnosis in an attempt to study the form, size, shape or position of the organs or parts of the organs of the body and to detect whether these fall within the normal range for the age and sex of the subject. In many instances one can decide whether the movements of the parts or their functions are normal or abnormal. Observations of abnormalities together with a knowledge of the possible pathology in the subject leads one to a diagnosis or to possible diagnoses which can lead to other types of investigation.

## The applications of X-rays: imaging

In conventional medical radiology X-rays are used to form an 'image' of the structures irradiated. An X-ray image will be formed by differential attenuation of the radiation if the structures irradiated differ in their thickness, density and in the nature and content of the different chemical elements present. The 'quality' of the image depends on geometric sharpness and contrast. Since the target is not a point source, the geometric sharpness of the image is governed in part by the effective size of the focal spot or area of the target or anode on which the electrons have been focused: blurring will increase with the distance of the object from the recording medium. Resolution of detail will also depend on the characteristics of the recording medium. Contrast is governed by the differing degrees of radiation attenuation in the object and on the contrast discrimination capability of the recording medium.

## Fundamental limitations

The limitations on the use of X-radiation in medical diagnosis are similar to those in industrial non-destructive testing, though with living biological material blurring of the image due to movement is almost always a factor. It is not possible to stop the movement of the heart and associated structures even if the patient holds his breath temporarily. It is not possible to stop peristaltic movements in the gastrointestinal tract or to prevent the movements of blood vessels and structures associated with the heartbeat. Patients, particularly children and those sick or injured, cannot always hold themselves still in the positions required for satisfactory radiography. It is therefore frequently more essential in medical diagnosis to use short exposure times than it may be in conventional non-destructive testing. Most medical exposures are fractions of a second or not more than two or three seconds in duration. To obviate movement blur completely would require exposures in the nanosecond range and although cold emission tubes are made capable of exposures of about 50 ns, their output is too low to obtain an adequate exposure unless many pulses are used and then the total exposure time is similar to those used with conventional generators (Ardran & Crooks 1974).

Another limitation in the medical field is caused by the low contrast obtained when radiographing all parts of the body with the exception of those with a high mineral content, for example the bones. Likewise, many of the soft tissue organs of the body, particularly when affected by abnormalities, are of unknown and irregular shape, which makes their recognition difficult. A further constraint is that biological material is affected by radiation: relatively high doses give rise to destruction of tissue, for example skin burns and eye lens cataracts, while lower doses can cause cellular damage resulting in chromosome changes or mutations. The latter can affect the male or female germ cells, causing genetic defects in future generations or neoplasms in any organ. It is for this reason that medical diagnostic irradiations must be kept as low as possible consistent with the immediate needs of the patient. As a result of the necessity of keeping exposure times short to obviate movement blur and to avoid adverse biological side-effects, images have to be recorded by the use of the minimum radiation. Since before the last war, systems have been available which recorded images whose quality was poor because of quantum mottle. This limitation was originally unrecognized but with the impending introduction of X-ray image intensifiers it was pointed out by Sturm & Morgan (1949) that their performance would be limited by quantum fluctuations resulting in degradation of resolution and contrast if X-ray intensities were reduced below those usually used at that time and the image observed after electronic intensification of brightness. Ardran & Crooks (1954) realized that the 'graininess' of radiographs taken with intensifying screens was primarily due not to film grain or intensifying screen grain but to a combination of statistical fluctuation of incident X-ray photons and screen grain, and postulated that there would be no significant increase in the speed of films or intensifying screens without loss of quality until screens could be made which had a higher initial absorption of X-ray photons than were available at the time. This was not generally believed until the phenomenon was rediscovered by Cleare, Splettstosser & Seemann (1962). The newer generation of intensifying screens, the rare-earth types, have resulted in a doubling of speed without significant loss of quality, but faster systems tend inevitably to suffer from an increase in quantum mottle. The use of metallic foils instead of salt screens has not been of value in the medical field.

*Methods of reaching theoretical limits*

(i) *Point source*

Ideally, to reduce geometrical blurring one should use radiation coming from a point source. To approach this the majority of X-ray tubes are of the line focus rotating anode variety. Nominal effective focal spot sizes commonly used vary between 0.3 and 2.0 mm. Originally, anodes were rotated at approximately 3000 rev/min depending on the mains frequency. For some years, whenever the financial constraints have permitted, anodes have been rotated at approximately 9000 rev/min, thus allowing a higher loading for a short period or the use of a smaller focal spot. To obtain the maximum loading for very short exposures the 'falling load' principle may be employed. For this purpose the generator delivers the maximum current at the commencement of the exposure, the current being decreased during the exposure just sufficiently to prevent overloading of the X-ray tube. The size of focal spot chosen has to be a compromise between the desired improvement in geometric unsharpness and the deterioration in sharpness due to movement blur which may result from the longer exposure time required with the smaller focal spot. The highest output possible with the selected focal spot should be used with the fastest recording system which will give an adequate image for the immediate purpose. The choice of focal spot size is always a compromise both on matters of physical principle and on finance. Microfocus X-ray tubes, both stationary anode and rotating anode, have been developed with focal spots between 10 and 100 μm. These tubes have a relatively low output but can be used with living material to give direct enlargement using a fast film–screen combination; because the structures are enlarged the unsharpness of the film–screen combination is effectively reduced. In living material this technique is of limited application.

(ii) *Contrast*

Because of the low inherent contrast (differential attenuation) of the soft tissue structures of the body, one can use lower voltages to generate lower energy radiation in an attempt to increase contrast. This will also reduce output so that exposure times increase and will result in less penetration of the part and thus a higher absorption of radiation with increased possibility of adverse biological effects. Radiation generated at 20–40 kV, frequently with a molybdenum target and with a molybdenum edge filter which results in much of the radiation being the 17.5 keV molybdenum characteristic, is used almost solely for examination of the breast which is a soft tissue structure with poor inherent contrast.

Contrast can also be increased, particularly in the thicker parts of the body, by the removal of scattered radiation. This is done by the use of scatter absorbing grids or by air gaps (15 cm or more) between the patient and the recording medium so that scatter is dissipated before it reaches the film. Scatter can be reduced by keeping the area irradiated as small as is consistent with covering the essential field and sometimes by compression of the patient which, by pushing tissue out of the way, reduces the volume irradiated and hence the scatter produced. There would be a considerable improvement in the quality of radiographs if patients were not obese; if all patients weighed 150 kg or more the standard of medical radiography would be considerably reduced.

The contrast discrimination of the recording medium can often be improved by the use of high contrast films and developing solutions. In practice, if relatively large areas of the body are being investigated, too great a contrast may mean that some of the structures are not adequately penetrated to form an image at all or that other parts are over-penetrated and the resultant film is too black to discern structure. Contrast can also be increased or reduced by using electronic means to produce the image, e.g. closed circuit television. Radiographs can also have their contrast altered by subsequent subtraction photographically or by electronic means; this is frequently time consuming and expensive but can be very valuable.

(iii) *Processing*

Attempts to produce good quality radiographs with minimum radiation will be frustrated if the films are not correctly processed. In the past, films were hand processed in thermostatically controlled tanks. Nowadays, automatic processors producing the dried film in between 90 s and $7\frac{1}{2}$ min are used for the majority of work. If relatively slow non-screen film is required for mammography or extremity radiography, hand processing will still have to be used since the emulsion on these films will not fix or dry adequately in automatic processors. When automatic processors were first produced a higher radiation dose was often necessary to produce the same film blackening as with hand processors but the modern versions can be as good or better than hand processing in this respect.

(iv) *Quality control*

In order to maintain a high standard of work and to reduce the number of repeat examinations due to poor quality films, which can be both costly and involve both patients and staff in unnecessary radiation, quality control procedures should be operated at all levels. This includes the performance of the X-ray equipment and the performance of films, intensifying screens and processing equipment. Variations in the true values of exposure factors as against the pre-selected ones may cause the voltage and current to be inaccurate by $\pm 10\%$ and exposure times can be inaccurate by 50 % at very short exposures, the inaccuracy decreasing with the length of the exposure time. X-ray films in different packs from the same manufacturer and of the same type may vary in speed by $\pm 20\%$, intensifying screens from the same manufacturer and type can also vary in speed by a similar amount. These factors may cancel each other out or they may add together to result in an exposure which can be up to double or half that which was required (Gibson *et al.* 1975). These facts make it difficult for operators to estimate correctly the exposure factors which should be used since the errors may be different at different times during the day.

Most large X-ray generators have automatic mains compensation; however, with three-phase generators the compensation may take place on only one or two of the phases. The voltages on the phases may not be the same and may vary between the phases from hour to hour (Ardran, Crooks & Birch 1978).

## X-RAY TECHNIQUES

### *Living but static subjects*

(i) *Conventional radiography*

Radiographs of the thinner parts of the body, for example, hands and feet, have in the past usually been made by exposing the film directly to the radiation which has passed through the part. This technique, usually referred to as a non-screen technique, uses a film with a thick emulsion with a high silver content on each side of the film base to absorb as much radiation as





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practical. Double emulsion films are used in radiography partly to increase their speed, partly to make thinner emulsions more readily processed and partly because one normally works with the original negative and if the emulsion were thick and only on one side, the film would readily curl when dry; because relatively large films are to be handled, this requires a thick tough base. Most other parts of the body are examined with a double emulsion, light sensitive film compressed between two salt intensifying screens. The film image produced is formed as a contact print from the transient light image produced by X-rays in the fluorescent material. With fine detail screens this technique is now largely used for the extremities because non-screen film is unsatisfactory with 90 s automatic processors. The use of intensifying screens results in considerable increases in speed varying from twice to 40 or more times that obtainable with non-screen film. This reduces both radiation exposures and exposure time and usually results in a higher contrast radiograph. The disadvantages are that the detail is impaired owing to the granular nature of the fluorescent salt together with the scatter of X-rays in the fluorescent material and the scatter of light which is emitted in all directions. Of course, with any double emulsion film there is scatter from one intensifying screen through the film to the other side and, if the radiation is not perpendicular to the film, parallax effects will be produced in the different layers of emulsion. For many years the commonest fluorescent material was calcium tungstate though zinc cadmium sulphide has also been used in the past. Barium lead sulphate was introduced after the last war and activated by strontium is still successfully used by at least one manufacturer. In the last few years, the rare earths, gadolinium oxysulphide terbium activated, lanthanum oxybromide thulium or terbium activated, and yttrium, or combinations of these, have become available (Ardran, Crooks & Fursdon 1976). Barium fluorochloride europium activated is also used. These new-generation screens have resulted in increases in speed of a factor of at least two for similar quality compared with what was possible in the recent past. Further increases in speed by additional factors of two or more are possible but with the fastest combinations one tends to suffer a granularity due to quantum mottle. Opinions differ as to how detrimental this may be to diagnosis and for many purposes many observers think that the advantages outweigh the disadvantages. The screens containing gadolinium emit a yellow–green light which for maximum speed requires a film primarily sensitive to this light whereas the lanthanum or barium type screens emit a blue light often containing ultraviolet, which can be used with conventional X-ray film. This new generation of screens is a major advance whether one considers it primarily of value to reduce patient and staff radiation dose or to enable one to use a lower X-ray tube loading which may result in shorter exposure times or the use of smaller focal spots or reduce the cost or wear and tear on a generator.

(ii) *Tomography*

Tomography is a term used when the X-ray tube, or subject, and film are moved in opposite directions while the exposure is being made. Objects in the plane of the axis of rotation about which the contrary movements are taking place remain relatively sharp whereas objects above and below this plane will be blurred to varying degrees. The definition obtained may be poor compared with conventional radiography but the ability to blur out structures above and below the selected plane is frequently of considerable value.

(iii) *Stereography*

A pair of stereo films may be taken of any static or relatively static object by making two exposures with the tube focus moved approximately 6 cm (distance between the eyes) between the exposures; the tube may remain fixed and the object tilted first in one direction and then to the same degree in the opposite direction to produce a similar effect. The resultant films are then viewed in a suitable optical stereoscope. This technique may be useful in studying objects with well defined edges and high contrast and in examining organs *post mortem* when the arteries or veins have been injected with high contrast material; it has not been found very valuable with low contrast living tissue.

(iv) *Colour radiography*

The use of colour film for radiography has from time to time been of interest. A suitable film with suitable processing will translate a given density range into a given colour and is most useful with an object of widely differing attenuation which would result in some parts being overexposed and blacked out. Colour film translates high densities into a readily transparent colour so that the whole object can be seen with one exposure instead of several with different penetrations. In the medical field this produces confusing results since the same anatomical structure when varying in thickness will be depicted in different colours or different anatomical structures, with the same attenuation, may be recorded in the same colour. In order to produce a useful range of densities it also means that the object has to be considerably over-exposed in part; for these reasons it has not been of real practical value in medical diagnosis. It is also expensive.

(v) *Photofluorography*

Photofluorography is the term used when the image is recorded by photographing a fluorescent screen image. This method has been used for mass radiography of the chest or stomach. Because all the light from the fluorescent screen cannot enter the lens of the camera, wide aperture optics have to be used and the most successful techniques have employed large concave mirrors. It requires a higher dose, 10–20 times more than that required for a full-sized film between intensifying screens. The small film used, originally 35 mm but now usually 70, 100 or 110 mm is relatively cheap and this is the main reason for its use. An image intensifier may be used instead of a fluorescent screen, though intensifiers large enough to cover an adult chest have not been developed. One of the reasons for the success of image intensification is that electron lenses can focus the light from a plane photocathode much more efficiently than can an optical lens.

(vi) *Xerography*

In this procedure the X-ray image is recorded by allowing the rays to fall on a charged plate, usually selenium. The radiation discharges the plate according to the attenuation of the beam and the resultant image is obtained by the effects of the discharge on a powder layer. This powder layer can be transferred to paper as a permanent record. It tends to produce high contrast images with varying degrees of edge enhancement and has been found useful primarily for examination of soft tissue such as the breast. It can produce very high quality images but the dose is higher than with some of the other techniques. It would have a wider use if it were



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less expensive and could operate at radiation exposures more equivalent to film–screen combinations.

*Moving organs*

(i) *Fluoroscopy*

Moving organs have been studied by the use of fluoroscopy since X-rays were discovered. Fluoroscopy is the viewing of a salt fluorescent screen irradiated continuously and is very valuable in studying movements of the heart and the gastro-intestinal tract and in enabling the observer to choose the best position for radiography. This procedure, which might last many minutes, can give a relatively high radiation dose to the patient and to the operator if he does not take suitable precautions. Nowadays, this is usually performed using an image intensifier with closed-circuit television to view the image. This has improved the quality and convenience of the procedure (dark adaptation of the observer's eye is not required) and can result in the use of smaller focus X-ray tubes and a reduction in radiation dose if used intelligently. Static films may be taken from time to time either with full-sized film or on 70–110 mm film through the intensifier. The image may also be recorded on videotape or cine film and viewed at leisure. The radiation may be pulsed and recorded on a video disc with immediate or delayed playback which can help to reduce dose. These items will be dealt with in greater detail by another contributor to this symposium. The ability to move the patient while he is being fluoroscoped enables one to use the parallax to determine readily whether one structure is in front or behind another. Stereoscopic fluoroscopy has been attempted using spectacles with motor-driven shutters to view alternately the images produced by two adjacent X-ray focal spots. The images produced by two alternately energized adjacent focal spots can also be viewed by using two television cameras presenting alternate images to the monitor. Stereoscopic fluoroscopy has not proved of practical value.

(ii) *Rapid serial radiography*

To record some moving organs, films may be exposed at the rate of 1–12 per second for a few seconds. Devices have been made to change full-sized cassettes or to use a full sized cut or roll film intermittently clamped between a pair of intensifying screens while the exposure is made or by the use of 70 or 100 mm film photographing a fluorescent screen or the output phosphor of an image intensifier. The size of film used, rather than the frame rate, distinguishes this from cinefluorography. Equipment moving full sized cassettes and roll or cut film tends to be cumbersome but has had advantages in giving higher quality films than was possible by cinefluorography, but with the advent of modern image intensifiers and cine cameras full sized films are less used.

(iii) *Cinefluorography*

Cinefluorography was first carried out in 1897 by using a cine camera to record a fluorescent screen image. This could not be widely used, until image intensifiers were developed, because of high radiation doses. With the advent of image intensifiers this became a practical procedure, the images being recorded at 1–200 or more frames per second, though usually at 25, 50 or 75 frames per second. This is a valuable procedure when studying rapidly moving parts such as the blood flow through the heart and lungs and for the swallowing mechanism in the mouth and pharynx, though this latter examination is now often performed by using a video tape recording of the fluorescent image. The cine film may be viewed at the speed at which it was taken, or at a slower speed, e.g. 16 frames per second, which will just remove flicker, or may be examined frame by frame. It can also be combined with other investigations such as pressure measurements or flow studies and this information can be correlated with the individual frame of the cine film. Some objects move relatively slowly, for example the contractions occurring in the large bowel between evacuations, and for this purpose time-lapse cinefluorography at 1 frame per minute can be carried out for a long period without undue patient dose. Cinefluorography has also been used to produce a three dimensional image by projecting alternate frames exposed by two adjacent focal spots using a red and green rotating shutter on the projector and wearing spectacles with one eye covered by a red filter and the other by a green filter. Similar techniques have employed Polaroid materials to obtain a similar effect. These three-dimensional techniques have not been found of great practical value. The principal developments in this field have been reviewed by Ardran (1973).

## Contrast agents

### *Naturally occurring*

When a part of the body is radiographed the bones are fairly readily seen because they contain minerals of high atomic number in high concentration. Calcification or mineralization may occur in other structures and may be either normal or abnormal; it occurs in cartilages of the ribs, the larynx and from time to time in other places. Calculi (stones) frequently contain calcium and thus may be visualized in conventional radiographs of the urinary tract, gall bladder or salivary ducts. Naturally occurring gas or air produces a negative contrast compared with soft tissue. It is for this reason that in a conventional radiograph of the chest one can distinguish the lungs from the heart, and the cavity of the pharynx, the larynx or trachea from the surrounding tissues. Gas or air may partly outline the stomach or large bowel. Fat has a lower attenuation than other soft tissues and when present in significant discrete amounts can sometimes be identified on the film.

### *Deliberately introduced contrast agents*

Air or gas (usually $CO_2$) may be introduced into cavities of the central nervous system (ventriculography or encephalography) to visualize the spaces normally occupied by cerebrospinal fluid. These gases can also be introduced into the stomach or large bowel or into the urinary bladder, the pleural, peritoneal or pericardial cavities to visualize their contours. Carbon dioxide is used whenever there is a potential danger of air embolism.

When an increase rather than a decrease in contrast is required, materials containing a high concentration of elements of high atomic number have to be used. Barium sulphate suspension is used as a barium meal for the examination of the oesophagus, stomach, small and large bowel. It has been used to examine the bronchial tree and for other purposes. Finely powdered metallic tantalum has also been used to coat the larynx and bronchial tree and as a marker during certain operations since it produces a high contrast for small quantity and appears to be non-toxic. Organic compounds containing high concentrations of iodine are used to examine the bronchial tree, the gastro-intestinal tract and the cavity of the uterus and Fallopian tubes by direct introduction. The same or similar compounds may also be injected into the arterial system to visualize the blood vessels of practically every organ in the body. The original compounds sometimes had toxic effects but with the ones in present use this is only a relatively small hazard. Some of these compounds can be injected into a vein when they will be excreted by the kidney or liver and used to visualize the urinary tract or the gall bladder. They can be introduced into the lymphatics, injected into the milk ducts of the breast or into practically any other organ which has a cavity which they can fill. These topics have been considered in detail by Knoefel (1971).

*Contrast agents not available*

The Philosophers' Stone of diagnostic radiology has been the search for a material of adequate radiopacity which could be introduced in the body and which could be taken up by particular normal or abnormal cells and be retained long enough for radiography to be carried out. Non-toxic materials of adequate radiopacity have not been found for this purpose or adequate quantities could not be introduced. Colloidal thorium dioxide was used as a contrast agent to visualize the cavities into which it was introduced but unfortunately it is very radioactive and when retained could produce neoplasms. It was taken up by the reticulo-endothelial cells in the liver, lymph glands, spleen and bone marrow in quantities which could be visualized. The type of contrast medium which could be taken up by certain cells preferentially exists today in the various radionuclides used in nuclear medicine. Sufficiently small quantities can be non-toxic and, if suitable materials are chosen, not sufficiently radioactive to be a hazard. Although the nuclear medicine techniques for imaging these small quantities produce an image which is poor in quality compared with a radiographic image, they can often produce a useful image when conventional X-ray techniques cannot produce one at all.

## Recent and future developments

Over the last 20 years nuclear medicine techniques have come into routine use for many purposes largely to fill in the gap left by the unsuccessful search for contrast agents which were non-toxic and could be usefully employed in very small quantities and in a quantitative manner. The more recent development of computerized tomography has resulted in a completely new dimension in X-ray diagnosis. I am among those who, if presented with the idea of this system, would have almost certainly come to the conclusion that it was unlikely to be useful in practice. I think it quite possible that the methods of beam analysis which it employs may well be applied to other radiological techniques with significant further advances. Electron radiography, ionography and the use of multiple proportional wire counters and avalanche discharge techniques alone or in combination may well in the future overcome some of our present limitations but these will be discussed in more detail by other contributors to this symposium.

Finally, it must not be forgotten that one of the difficulties in examining images is the inability of the observer always to see what is visible or to interpret it correctly. Diagnostic radiology from its inception has suffered from the difficulties which are common to any process where images have to be observed and interpreted. Radiologists are always asking for better quality images but there are many occasions where if too much detail is shown it may be difficult to see the wood for the trees; it can be very difficult to see a piece of straw in a haystack.

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