PRINCIPLES OF X-RAY DIAGNOSIS

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LONDON

BUTTERWORTHS

ENGLAND:	BUTTERWORTH & CO. (PUBLISHERS) LTD. LONDON: 88 Kingsway, W.C.2
AUSTRALIA:	BUTTERWORTH & CO. (AUSTRALIA) LTD. SYDNEY: 20 Loftus Street MELBOURNE: 473 Bourke Street BRISBANE: 240 Queen Street
CANADA:	BUTTERWORTH & CO. (CANADA) LTD. TORONTO: 1367 Danforth Avenue, 6
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SOUTH AFRICA:	BUTTERWORTH & CO. (SOUTH AFRICA) LTD. DURBAN: 33/35 Beach Grove

Suggested U.D.C. Number 616–073·75

Printed in Great Britain at the Pitman Press, Bath

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PREFACE

This book is intended as an introduction to the system of observation and deduction by which a radiologist makes his diagnosis from radiographs. It is primarily intended for those who have just begun a full-time course of radiology. It is also to help candidates for such postgraduate qualifications as the M.R.C.P. and F.R.C.S. and senior medical students who wish to understand the principles that lie behind diagnostic radiology without getting bogged down by descriptive details. The book does not aim to give the radiographic features of various diseases, although there are occasional brief descriptions to illustrate the principles outlined. On the grounds that ' one picture is worth a thousand words ', the text has been kept as short as possible. Three hundred and sixty-eight radiographs have been illustrated and there are 62 diagrams.

The first two chapters summarize the few relevant principles of physics and of interpretation that need to be clearly understood if the appearances in radiographs are to be fully appreciated. Subsequent chapters set forth the main principles by which an accurate diagnosis may be reached in the various parts of the body. Although a book of this kind is mostly concerned with disorders that are common, rare diseases have been mentioned where they illustrate points of general relevance. Necessarily the decision to include or omit some factors of secondary importance has been a personal one. The guiding influence in such instances has been my personal experience of teaching and of the needs of postgraduate students. References to other literature have been omitted to keep the book as concise and simple as possible. A guide to further reading is given on page 278.

DAVID H. TRAPNELL

ACKNOWLEDGEMENTS

I am greatly indebted to all the radiologists who have taught me and whose writing has inspired and enlightened me. I am particularly grateful to my former teacher, Dr. George Simon, whose logical analysis of radiographs—based on his vast knowledge of clinical medicine, morbid anatomy and practical radiology—encouraged me to think and write about the principles upon which the daily work of every diagnostic radiologist depends.

I am indebted to the following for permission to reproduce the Figures indicated: Messrs. Kodak Ltd. *1* and *3*; Messrs. Butterworths and Dr. George Simon *29, 32, 33, 39, 40, 46, 47, 49, 50, 52, 56, 57, 59, 61, 63, 84, 86, 87* and *88* from *Principles of Chest X-ray Diagnosis*, 2nd edition, and *172, 173, 174, 175, 176, 177, 179, 181, 182, 183, 184, 187, 188, 189, 191, 193, 198, 201* and *203* from *Principles of Bone X-ray Diagnosis*, 2nd edition; Messrs. Butterworths and Dr. G. H. Du Boulay *207, 208, 209, 210, 211, 212, 213, 214, 215, 216, 219, 220, 221, 222, 224, 225, 226, 227, 228, 229, 232, 234, 235, 236, 237, 238, 239, 240, 241, 242, 243, 244, 247, 257, 258, 259* and *269* from *Principles of X-ray Diagnosis of the Skull*; Dr. F. Starer *130, 147, 164, 165, 262, 268* and *279*; Dr. G. F. Swann *261, 263, 264, 265, 266, 267, 270, 271* and *272*; Mr. N. R. Barrett *90*; Dr. J. C. Chartres *296* and *297*; Dr. L. Davison *149*; Dr. L. Pell *157*; Dr. J. Rhodes *153*; Dr. J. H. Walters *132*; Dr. W. White *302*; the Editors of *British Journal of Radiology 295, 296* and *297*; the Editors of *Clinical Radiology 285, 286* and *287*; the Editors of *Thorax 60*.

The Departments of Medical Photography and Illustration at Westminster Hospital and Queen Mary's Hospital, Roehampton, kindly copied the radiographs and Miss Jill Hassell drew all the line diagrams except *Figure 285*, which was drawn by my wife. I am grateful to Miss K. M. Prior for her invaluable assistance with the correction of the proofs and to many of my colleagues who offered their help and advice in the earlier stages of the book.

The publishers have helped me at every stage of production and made the task as painless as possible.

Last but not least, I must record here, too, my gratitude to my wife whose endless patience and encouragement made possible the writing of this book.

CONTENTS

CHAPTER 1

MAKING RADIOGRAPHS

HOW RADIOGRAPHS ARE PRODUCED

Radiographs, like photographs, must be made correctly if they are to be useful. It is thus essential for those concerned with the interpretation of radiographs to understand the principles which relate to the exposure and processing of the x-ray film. It is particularly important for radiologists to be so thoroughly familiar with the factors concerned in the production of a useful radiograph that they are able to help their radiographers obtain the best radiographs possible in the worst circumstances. The purpose of this chapter is, therefore, to explain the fundamental physical principles involved in the formation of a radiographic image.

The Production of X-rays

X-rays are part of the so-called electromagnetic spectrum. Radio and television waves, which are also part of it, have a long wavelength and the x-rays used in medical radiography have a wavelength about 20,000 times less than that of visible light (*Figure 1*). Because their wavelength is so small, x-rays can penetrate materials which do not transmit visible light.

Atoms consist of a central positively charged nucleus around which electrons move in orbit rather as the planets do around the sun. Each electron has a negative electrical charge. Because a complete atom has no polarity (charge), it follows that the positive charge of the nucleus is equal and opposite to the total negative charge of all the electrons around it. The atomic number of an element is, in fact, a statement of the number of electrons present in an atom of it. Thus a hydrogen atom has one electron, an oxygen atom has eight electrons and a lead atom has 82.

Electrons may be made to escape from their atoms in a number of ways. In order to produce x-rays a metal is heated to incandescence so that electrons ' evaporate ' from the surface of the hot metal, a process called thermionic emission. Because these electrons have a negative charge, they are attracted to a positively charged structure.

An x-ray tube (*Figure 2a*) basically comprises a metal element (cathode) which can be heated to incandescence and a metal target (anode) which can be made electrically positive to the cathode. To obtain x-rays with the greatest efficiency, the tube must be evacuated as completely as possible and a high voltage applied between the negative cathode and positive anode. Then, when the cathode filament is heated, a beam of electrons is generated which strikes the anode and x-rays are produced. The efficiency of the best x-ray tube available is poor because most of the energy put into the tube is converted into heat in the anode. Modern x-ray tubes therefore include a motor to rotate the anode, the metal of which has a very high melting point. This makes it possible for a fine stream of electrons to strike a small area (the focal spot) on the anode while the heat liberated is spread over a much larger area (*Figure 2*). Even so the anode of an x-ray tube in use may become white-hot.

The size of the focal spot influences the definition in the radiograph obtained (*see* page 7). Just as a point source of light casts sharp shadows while a larger source of illumination blurs the edges of the shadows, so the smaller the focal spot on the anode of the x-ray tube, the sharper the shadows in the radiographs produced. However, it is obvious that the smaller the focal spot, if other things remain the same, the greater will be the tendency to overheat the anode. For this reason various types of x-ray tube are now available with different sizes of focal spot. Most tubes available today permit one of two spot sizes to be selected to suit the purpose for which the tube is to be used.

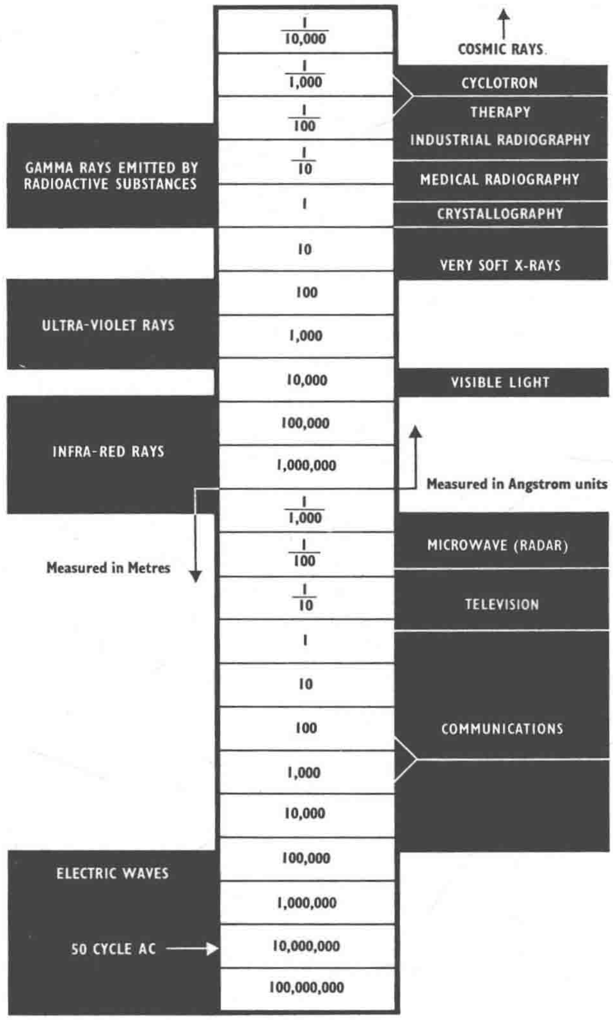


Figure 1. The electromagnetic spectrum

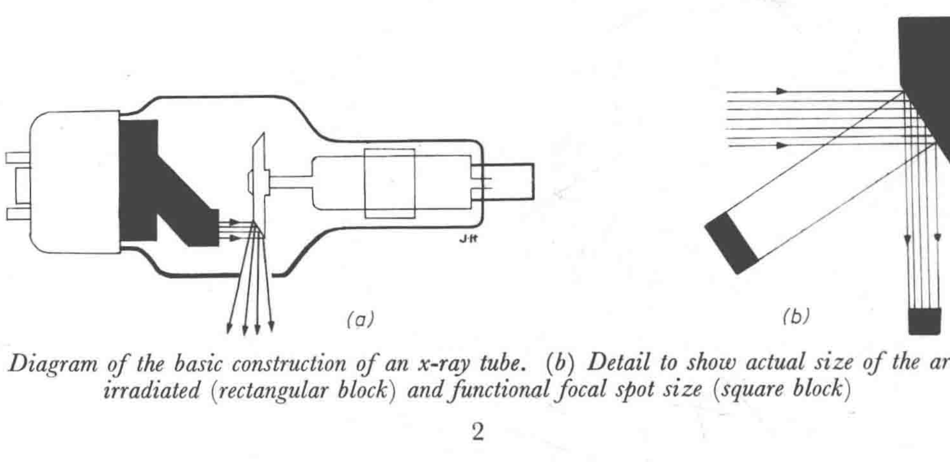


Figure 2. (a) Diagram of the basic construction of an x-ray tube. (b) Detail to show actual size of the area on the anode irradiated (rectangular block) and functional focal spot size (square block)

The apparatus necessary to make the x-ray tube work consists essentially of a transformer and a rectifier to produce direct current at very high voltages (50,000–150,000 volts, usually measured as kilovolts, i.e. 50–150 kV) and a low-voltage circuit to heat the cathode filament. The current needed to heat the cathode is quite large (3–6 amps) compared with the current actually flowing between the cathode and anode, which is very small and therefore measured in milliamps (1 milliamp or mA = 1/1,000 ampere). The greater the current flowing through the cathode, the hotter it becomes and therefore more electrons—and thus more x-rays—are produced. The more the voltage between the cathode and anode is increased, the faster the speed with which the electrons leave the cathode and strike the anode target and thus the greater the energy of the x-rays generated. It will be apparent, therefore, that variations in the cathode current cause changes in the tube current (mA), and thus in the *quantity* of x-rays produced. Alterations in the voltage applied between the cathode and anode mostly affect the *energy* (penetrating power) of the x-ray beam (although increases in voltage also result in some increase in the quantity of radiation produced).

The Formation of the Radiographic Image

The radiograph exactly corresponds to a photographic negative. It consists of a transparent base coated on both sides with an emulsion containing fine particles of what is known as a silver halide (mostly a mixture of silver bromide and silver iodide). When light or x-rays strike these particles they are changed so that, after development, the grains exposed to light or x-radiation appear black while those not exposed are dissolved away from the film in the fixing solution. Various types of film are now available whose emulsions are more or less sensitive to various colours of light and to x-rays. Different sizes and numbers of silver halide grains can be incorporated in the film emulsion. The clarity or definition in a radiograph is greater if many small grains are present and less if there are a few large ones. The larger grains, however, respond more rapidly to the light striking them and they are therefore used in the so-called ' fast ' films in which definition is poor, but the exposure needed is small.

Fluorescence and its Applications

In addition to their effect upon the silver compounds used in the emulsion of x-ray films, x-rays cause certain substances (such as calcium tungstate and barium platinocyanide) to fluoresce—that is, to produce visible light. The quantity of light produced by small quantities of x-radiation (which would remain safe for the patient if used for more than a second or so) is so small that it can be seen by the human eye only in a darkened room. When the eye has become adapted to low light intensities, it can easily detect such fluorescence and it is this principle which is used in fluoroscopy (often called ' screening '). This consists of directing a beam of x-rays through the patient so that they strike a layer of some fluorescent material which is viewed by the radiologist through a sheet of lead glass (which prevents the x-rays from reaching his head and eyes). The principal use of such a technique is for the examination of moving objects and for the detection of abnormalities in structures, such as the stomach, where conventional radiography may not demonstrate the abnormality present because of its position.

The quantity of light produced by fluorescent materials is proportional to the quantity of x-rays striking them. Because of this and because the silver compounds in x-ray films are more sensitive to light than they are to x-rays, radiographs of thick parts of the body are made by placing the film in a light-proof holder (cassette) between ' intensifying ' screens containing numerous grains of calcium tungstate. The blackening of radiographs made by means of such intensifying screens is practically all due to the light resulting from the fluorescence of the screens on each side of the film, only about 5 per cent of it being caused by the x-rays themselves. The effect is to reduce slightly the clarity and definition of the radiographic image obtained. An advantage of their use, on the other hand, is that the quantity of x-rays needed to produce a satisfactory radiograph (and thus the radiation dose to the patient) can be reduced by at least four times.

Image Intensification

While considering the applications of fluorescence it is appropriate to refer briefly to image intensification, although this is used mostly for fluoroscopy and ciné radiography.

Modern apparatus makes it possible for the brightness of the fluoroscopic image to be greatly increased by the use of an image intensifier tube. This is an evacuated glass tube, the end nearest to the patient having in it a fluorescent screen in intimate contact with a

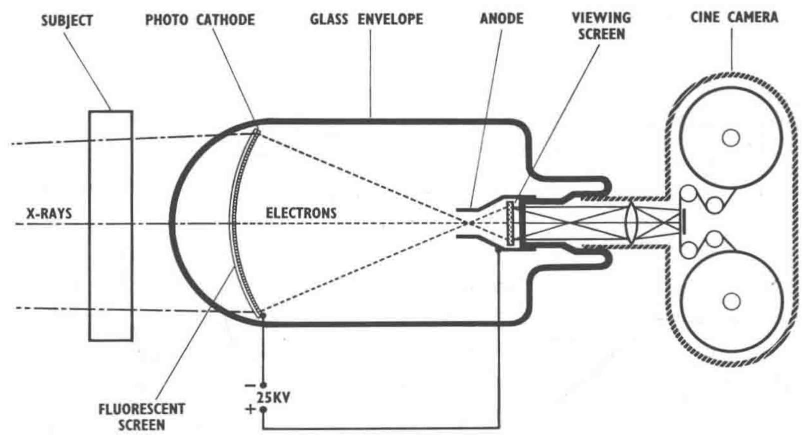


Figure 3. Diagram showing the construction of an image intensifier tube

photocathode. The latter emits streams of electrons in proportion to the light (which is proportional to the quantity of x-rays reaching it) produced by the adjacent fluorescent screen. These electrons are then accelerated and focused by a large potential difference (25 kV) between the photocathode and the anode, within which is a small fluorescent screen viewed by a television or ciné camera (*Figure 3*). By this means the brightness of the image can be increased about 1,000 times. At the same time its size is reduced, but optical or electronic apparatus can then be used to magnify the image so that it can be examined directly with the eye or displayed on one or more television screens.

The increase in the image brightness makes possible a great reduction in the amount of radiation necessary to produce a satisfactory fluoroscopic image and thus makes such techniques as ciné radiography practicable and safe. It is no longer necessary for fluoroscopy to be performed in total darkness, which means that time is saved (because there is no need for dark adaptation) and practical procedures, such as salpingography and cardiac catheterization, are made easier.

ASSESSING THE QUALITY OF A RADIOGRAPH

The first thing to decide on looking at a radiograph is, 'Does it show what it should?' Is the right anatomical part of the patient *clearly* displayed? If the part is present, but is not clearly shown, the cause of this lack of clarity must be decided in order that the fault in the radiographic technique can be put right.

Density (Blackening)

With an unsatisfactory radiograph one must first consider the black and white parts. Is the overall colour too black or too white? In other words, is the density too great or too little? Excessive blackness in the radiograph indicates that too much radiation has reached the x-ray film, while an overall whiteness or pallor shows that the exposure to the x-rays was too small. In either case there are two factors to consider (*see* Table 1; *see also* Contrast, page 7). Processing can also affect the density of the film (*see* page 10).

TABLE 1

Too black	*Too white*
Too large a tube current (mA) and/or too long an exposure time } i.e. mAs too high or too high kilovoltage (kV)	Too little mA and/or exposure } i.e. mAs too low or too low kV

Radiographic Exposure (mAs)

Blackening of x-ray film is proportional to the amount of radiation reaching the film, where voltages of the kind used in diagnostic radiology departments are concerned. The total quantity of radiation is determined by the duration of the exposure (usually measured in seconds or fractions of a second, and called the exposure *time*) and the *amount* of current flowing through the x-ray tube, which is measured in milliamperes (mA). The total exposure is therefore measured as the multiple of these two factors and is known as milliampere seconds (mAs). If, for example, the quantity of radiation is doubled and the exposure time halved, the total exposure remains the same if the kV remains constant.

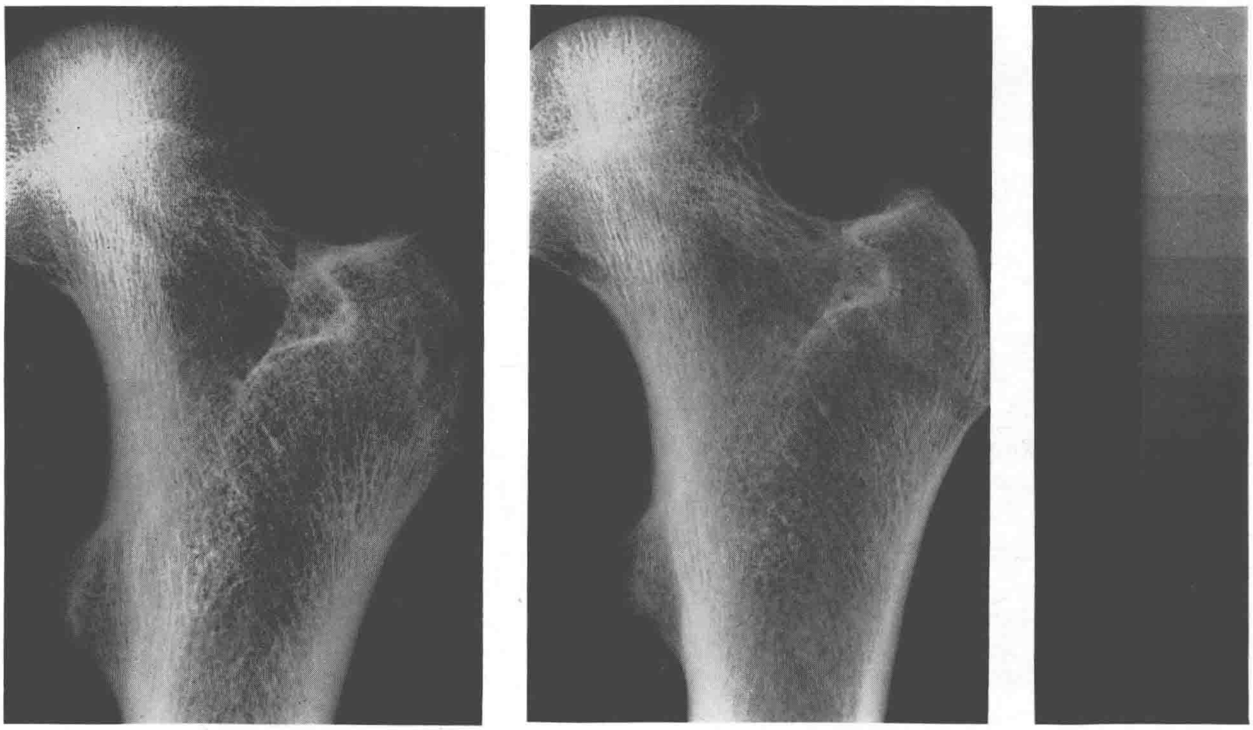
Kilovoltage (kV)

As the kilovoltage is increased, the x-rays generated have more energy and therefore greater penetration. The result is that more radiation passes through the part of the patient concerned and so reaches the film. In the range of about 50–85 kV, an increase of 10 kV approximately doubles the film blackening. This is in part, however, the result of the increased quantity of radiation produced (*see* page 3).

Because the varying densities seen in radiographs are due to different amounts of radiation being absorbed by various tissues, it is obvious that density differences—referred to as contrast—will normally be maximal when the kV is low (*Figure 4*). As the kV is increased, a greater proportion of the x-rays penetrates even the most dense structures such as bones; as a result, all parts of the radiograph are blackened, so that the contrast between the various tissues is reduced. With increasing voltages, the difference in the quantity of x-rays absorbed by various types of tissue is progressively reduced so that at very high voltages (over 1 million volts) all body tissues absorb the same amount of radiation. This is why voltages in the range 40–150 kV are normally employed in diagnostic radiology and much greater voltages are used for radiotherapy.

It is relevant at this stage that absorption of x-rays by different materials depends wholly upon the average atomic *number* (not the atomic weight) of the elements of which they are composed. Bones appear whiter in radiographs than muscle, for example, because they contain calcium (atomic number 20) and phosphorus (atomic number 15), while muscle, composed of carbon (6), oxygen (8) and hydrogen (1), has an average atomic number of about 6. A gold ring on a finger appears very dense (white) because its atomic number is 79, but the diamond mounted in the ring, being pure carbon, casts no shadow. (It will be apparent, therefore, that it is a waste of time to try to locate by radiography a sweet in the oesophagus or a fruit pip in the abdomen. Glass may or may not be opaque depending on its composition and the density of the tissues around it.)

In the light of this information it should be possible to say that a certain radiograph is too black, for instance, because the exposure (mAs) was too great, if contrast is still present between different tissues when the radiograph is viewed with a bright light; or because the voltage (kV) used was too high, when contrast is poor. Such conclusions can be made,



(*a*) (*b*) (*c*)

Figure 4. Radiographs demonstrating effect of variations in kilovoltage on contrast. (a) The upper end of a femur using 45 kV. (b) The same bone using 90 kV. The degree of contrast between the various parts of the bone is less clearly shown. The hole through the head and greater trochanter (through which a wire passed to join it to the rest of the skeleton) is much more clearly visible. Air is always well shown in the body in radiographs made with a high kilovoltage. (c) Radiographs (here joined together) of an aluminium step wedge. On the right the gradations of density are easily distinguished at 45 kV. On the left, at 90 kV, the contrast between the various densities is almost eliminated

however, only if it is known that the processing of the film was correct (*see* page 10). Part of the skill of radiography lies in choosing a suitable mAs and kV for each part of the body.

Sharpness (Definition)

It may be that a radiograph is of satisfactory density (blackness) and gives normal contrast between the various tissues, but that it is still of no value because the outlines of the structures shown are blurred and indistinct. Such a lack of sharpness or ' crispness ' in the radiographic image may be the result of:

(1) *Movement of the patient* during the exposure.

(2) *Movement of the film* during the exposure.

(3) *Movement of the x-ray tube* during the exposure. This normally occurs only with small apparatus such as portable and dental machines.

(4) *A large focal spot* (*Figure 5b*) in the anode of the x-ray tube. The greater the size of the spot, the wider becomes the penumbra around an object, particularly if the object–film distance is large.

(5) *A large object–film distance* (compare *Figures 5b* and *6b*), usually because for some reason (such as a splint, mattress or dressing that could not be moved) it was impossible to bring the film closer to the patient.

(6) *A small anode–film distance* (*Figure 6a*). Sometimes, in operating theatres for example, it is possible to obtain a radiograph only if the tube is close to the patient. This means that the x-rays striking the film are more divergent than usual. Normally radiographs are made with the film at 36–40 in. (1 m.) from the anode, when the resulting magnification of the image is so slight as to be irrelevant. Chest radiographs are usually made at 60 or 72 in. (2 m.) to obtain the best quality image without magnification. In most departments it is impracticable to make standard radiographs of other parts at such distances because the x-ray tube has to be so high above the x-ray table that the radiographer cannot reach it.

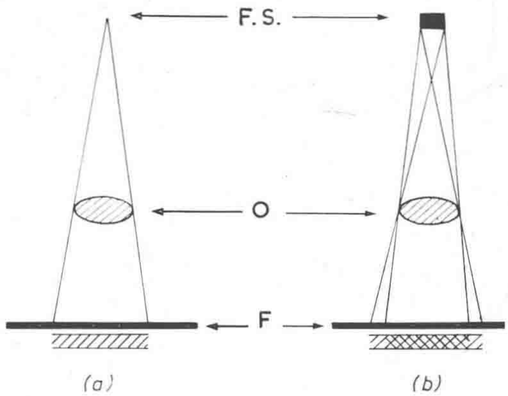


Figure 5. Effect of focal spot size on the sharpness of the radiographic image. A large focal spot (b) causes a penumbra at the edges of the shadow

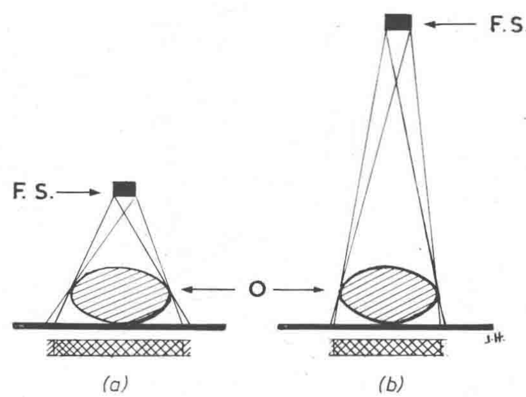


Figure 6. Effect of variation in the focal spot–film distance. If the object is near the film, even a large focal spot causes a small penumbra (b), whereas the same size focal spot near the film causes a larger penumbra (a)

(7) *Other radiographic factors* such as the kind of film and intensifying screen used. ‘ Fast ’ films have large silver halide particles in their emulsion (*see* page 3) and therefore reveal less detail, but at the same time they require less exposure than ‘ slow ’ emulsions which have fine grains. Similarly, screens (*see* page 3) contain grains of calcium tungstate, ‘ fast ’ screens having larger grains than ‘ slow ’ ones. By the use of ‘ fast ’ films and screens a short exposure time may be possible, but the definition in the radiographs will be correspondingly reduced. At the other end of the scale, for thin parts of the body, such as the hand, it is possible to use a film with fine grains in its emulsion without intensifying screens at all and so to produce a high definition (‘ sharp ’, ‘ crisp ’) radiograph. Obviously the detail that can be obtained depends ultimately on the size of the halide grains in the film emulsion. Details smaller than the smallest grains cannot be shown.

Contrast

The contrast, or difference in radiographic density, between various structures shown in a radiograph depends partly upon radiographic factors and partly upon the inherent differences between the structures themselves, particularly in their average atomic number. Tissues such as bone, for example, absorb more radiation than soft tissues such as liver or muscle, and thus appear white; the latter in turn absorb more radiation than fat and gas, which thus appear blackest.

As the kV is increased, more and more of the x-rays pass through all the tissues present to reach the film, and the contrast between the different structures is reduced (*see Figure 4*). Similarly the thicker the part of the body irradiated, the more the x-rays are scattered within it, thus reducing the contrast between the various shadows obtained. The area of the part irradiated is therefore kept as small as possible by collimation (restriction) of the x-ray beam by means of cones or diaphragms. Scattered radiation reaching the film from thick parts of the body can be largely eliminated by the use of fixed or moving grids, but this necessitates a greater exposure (*see below*).

SCATTERED RADIATION

When x-rays strike matter some are absorbed, while others ' bounce ', changing their direction and losing some of their energy. The effect of this scattered radiation, if it reaches the film, is to cause fogging and thus reduce the contrast and definition. In order to maintain a high quality in radiographs, scattered radiation reaching the film must be reduced to a minimum. Several means of achieving this are available.

Beam Collimation

The area of the primary x-ray beam should be strictly limited to the area of the film by the use of the light beam diaphragm or cones attached to the x-ray tube. This means that only the part to be examined is irradiated and that there is therefore virtually no scattered radiation from neighbouring (irrelevant) structures. Beam restriction is also of value and importance because it minimizes the radiation dose received by the patient.

Grids

A grid is a thin sheet of material which is not opaque to x-rays and in which there are embedded numerous very thin strips of lead. These are arranged so that they are parallel to each other and their edges are towards the surface of the sheet. As *Figure 7* shows, the

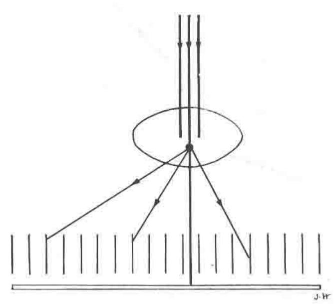


Figure 7. Diagram showing how a grid, here represented by the vertical parallel lines, absorbs scattered radiation, but allows direct radiation to pass through it to the film

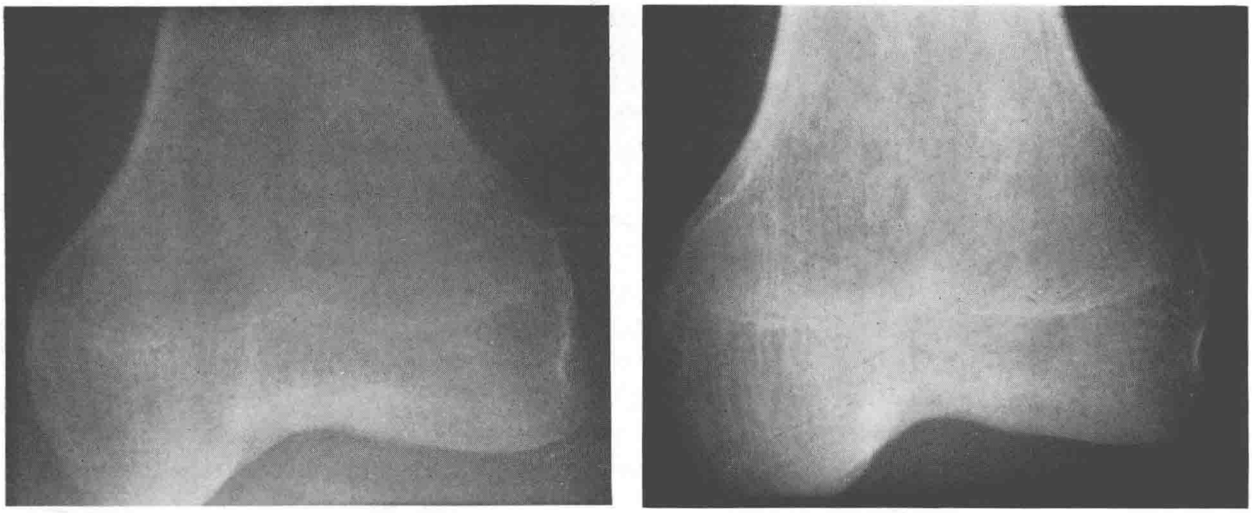
effect of these lead strips is to absorb most of the radiation that is not passing straight through the gaps between them. Direct (primary) x-rays continue to pass through the grid unhindered while oblique (scattered) radiation is absorbed.

Some grids are constructed so that all the lead strips are slightly tilted inwards at their top edges, allowing the divergent (primary) x-ray beam to pass through unhindered. These are called focused grids; they will obviously be effective only when used at the correct distance from the anode with the correct face uppermost.

Grids are placed as close to the film as possible and, if they are stationary during the radiographic exposure, cast a characteristic shadow in the radiograph. The whole film has numerous parallel white lines on it, corresponding to the thin lead strips in the grid. To avoid these shadows, the grid can be made to move across the film one or more times during the exposure in a device called a Potter–Bucky diaphragm. The speed at which the grid moves must be adjusted to the duration of the exposure so that the shadows cast by the lead strips are evenly blurred throughout the film. Because the x-ray tube, the patient and the film remain stationary, the final radiograph shows high definition.

The exposure necessary to produce a satisfactory radiograph is higher than that needed when no grid is used. However, the detail visible with a grid is so much greater, particularly in thick parts of the body (*Figure 8*), that its use has become a routine when radiographing most areas.

The higher the lead strip and the narrower the gap between strips, the more effective the grid becomes as a filter for scattered radiation. This relationship—the height of the strips



(*a*) (*b*)

Figure 8. Radiographs of a bone in a soft tissue phantom, (a) without and (b) with a grid. Contrast is obviously greater when a grid is used because the scattered radiation is absorbed

to the width of the gap between them—is called the grid ratio and may vary from 5 :1 up to 16 :1. High-ratio grids are essential if high kilovoltages are to be used because the direction of scatter from high-energy x-rays is forwards.

PRACTICAL PROBLEMS OF RADIOGRAPHY

It will be apparent from the foregoing that there are a number of factors which influence the quality of any radiograph. These are obviously related and, at times, opposed to each other. The skill of a radiographer lies, therefore, not only in putting the patient in the correct position, but in choosing the type of film and the exposure, kilovoltage, anode–film distance, etc., which will produce the best results.

An illustrative case may help to show how such problems are solved in practice.

An elderly, breathless and rather confused man has to have his chest radiographed. His deafness and confusion make co-operation with the radiographer difficult. His gangrenous leg renders standing impossible, and his cardiac failure and chronic bronchitis combine to make him very breathless. To add to the radiographer's difficulties, this particular patient is obese as well as deaf.

The sort of approach that will best succeed is as follows. The radiographer first talks to the patient to explain to him what she wants him to do. If appropriate, she can reassure him that he will not be hurt or kept in the department longer than is really necessary. She then helps him from the wheel chair on to a wide, strong stool where he can sit securely and tolerably comfortably with his chest facing the x-ray film cassette and his knees under it. To aid him to remain in this position a cloth band is firmly fixed round the back of his chest from one side of the cassette stand to the other.

Having put the x-ray tube in position 6 ft. from the patient and set the diaphragm to limit the irradiated part of his body to the area of the x-ray film, she explains to him that he must stop breathing while the picture is made. As she does so, in this case, she is aware that such a request is going to be met with the minimum of co-operation. Nonetheless she tries but, as she feared, no amount of rehearsing will stop this patient breathing.

The radiographer now has several choices. She can let the patient continue to breathe and try to obtain a very short exposure time (0·01 second, for example) in order effectively to stop all movement. Because the man is large, however, and because the x-ray set is old and will not emit enough x-rays in such a short time to produce adequate blackening of the film, this course proves to be impossible even when 'fast' film and intensifying screens are used. She then tests the machine to see if by increasing the kV (and thus knowingly losing contrast) she can obtain a sufficiently short exposure to get a radiograph which shows no blurring due to the patient's movement.

She now returns to the patient to secure his help in another way. He is asked to breathe through his mouth and hold his nose tightly between his right thumb and index finger. Into the better of his two deaf ears she then shouts, 'Shut your mouth'. For a second or so the patient obeys and does not breathe. This gives enough time to obtain a satisfactory radiographic exposure, although it means that his two shoulders will not be shown symmetrically in the film because his right hand is raised to hold his nose behind the cassette. The radiographer still makes the exposure time as short and the tube current as high as the x-ray set will permit, to minimize the effect of any movement that does occur during the exposure.

The radiographer goes to see the film after it has been processed. Although, in the circumstances, it is satisfactory, it is not perfect, since the chest is slightly rotated and the right scapula is partly projected over the upper part of the right lung because the patient's right hand was raised to hold his nose. In the left mid-zone of the chest is a solid-looking opacity. She therefore decides that a lateral view is needed (*see* page 16) to locate the lesion causing the shadow.

Now, because the exposure needed is much greater, it is impossible to prevent the patient breathing for long enough. The radiographer therefore moves the x-ray tube nearer to the film. This reduces the necessary exposure (because the intensity of x-rays, like that of light and heat, decreases in proportion to the square of the distance they travel), but will cause slight distortion and blurring in the final radiograph. At 48 in. an exposure short enough to arrest respiration and movement with the patient's co-operation is achieved, but at the price of the loss of some detail in the lateral view.

This illustrative case has been described at some length to show how difficult it may be in practice to obtain a good radiograph that may so easily be requested and the quality of which may so easily not be appreciated.

PROCESSING RADIOGRAPHS

Thus far we have been concerned with how the radiographic exposure is made and the factors which influence it. The process by which a permanent image is made visible in the radiographs is clearly equally important. Fortunately the principles involved are simple and the possible variations fewer than those involved in recording the radiographic image.

The first stage of film processing is development. The dry and as yet apparently unaltered x-ray film is removed from the cassette or paper envelope, placed in a convenient frame and immersed in developing solution (which essentially consists of a reducing agent, metol and hydroquinone). This makes the latent, invisible image in the radiograph appear by converting silver halide grains of the film emulsion which have been exposed to radiation (or light from intensifying screens) to metallic silver, which appears black and opaque.