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MINI-SYMPOSIUM: RADIOLOGY FOR THE FRCS (Orth)

(i) Ionising radiation and orthopaedics ☆

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Summary Ionising radiation is a dangerous and potentially lethal modality yet its use is vital to surgical practice and patient care. It is necessary for the surgeon to understand the physical properties of ionising radiation and its effects on living tissue leading to the risk of induction of carcinogenesis and somatic effects such as cataract formation. These risks justify the statutory regulations that control its use, the need for protective equipment and garments and surgeons' responsibility to minimise and monitor their radiation exposure together with that of patient and staff. These aspects are discussed in detail so that ionising radiation may be safely used in the workplace to the benefit of patient care with very minimal risk to surgeons and their staff.

Introduction

Roentgen discovered X-rays in 1895 and in the medical setting X-rays developed pari passu with surgery with an explosive expansion in the last two decades. In orthopaedics X-ray usage increased dramatically with the concept that accurate operative reduction and rigid fixation of fractures, often with the necessity of X-ray imaging, hastened recovery and shortened hospital admission times. During this period radiation education and protection practices lagged behind the clinical scene and the situation was worsened in that many hospital authorities were slow to accept their responsibility of the radiation protection of their staff. The recent finding of a cluster of Australian orthopaedic surgeons with thyroid cancer has highlighted the problem.[1]

That ionising radiation causes cancer is well established from the Second World War atomic explosions[2] and the Chernobyl accident that saw a near 200-fold increase in childhood thyroid cancer.[3] Thyroid cancer occurring after a latent period following radiotherapy to the face for acne, the scalp for tinea capitis and the

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tonsillar bed for chronic infection is well recognised.

The link between radiation and thyroid cancer has a documented genetic basis with a high incidence of the RET/PTC thyroid specific oncogene being described in children from the Chernobyl region.[4] This oncogene has been produced from both *in vivo* and *in vitro* radiation exposure.[5]

This risk of cancer from exposure to radiation and the radiation somatic effects cannot be ignored and demands an understanding of the modality by surgeons with a continuing education process and a constant awareness and reaction to the risks throughout a surgical career.

Physical properties and generation of X-rays

The X-ray tube, where X-rays are produced, is made up of a cathode and an anode, encased in an evacuated glass container which has a window for the X-rays to emerge but is otherwise encased in lead to prevent radiation escaping in all directions. The cathode is a filament that is heated by the passage of an electric current. The heat promotes electrons to leave the surface of the filament. A high potential of more than 50,000 V between the cathode filament and the anode accelerates the electrons from the filament and fires them towards the anode, called the target. The electrons hit the target anode and in the deceleration process electromagnetic radiation in the form of X-rays (bremsstrahlung or braking radiation) and heat are produced. See Fig. 1.

A cooling system, normally using oil, is used to remove the large amount of heat generated where the electrons strike the target. The anode is made to rotate so that the heat and continuous bombardment do not damage it by constantly striking it at one spot. The target anode is normally made of tungsten as its higher atomic number allows the production of a greater number of X-rays. The X-rays are "filtered" on emerging from the X-ray tube by the glass window material (inherent filtration) and by other materials such as aluminium placed at the outlet (added filtration). This "filtration" removes the low energy X-rays that are useless in image production and only contribute to the unwanted exposure of the patient and staff.

The spectrum of X-rays generated consists of the continuous bremsstrahlung X-rays as well as some "characteristic X-rays". The latter are so-called because they are characteristic of the target material (tungsten).

The high voltage (kV) controls the energy or penetrating power as well as the number of X-rays

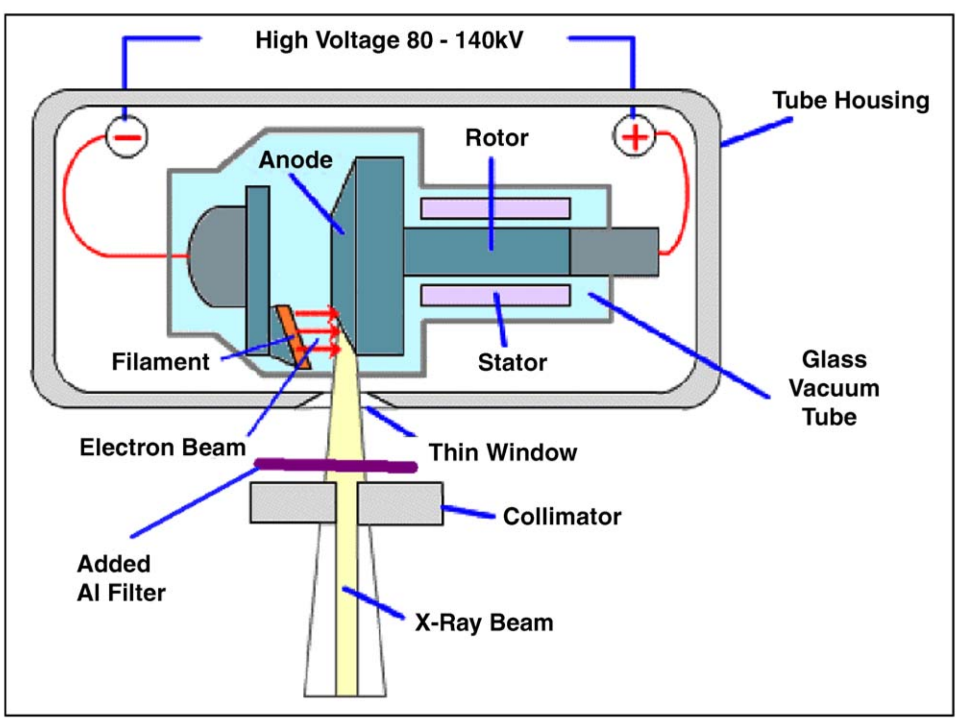

Figure 1 Schematic diagram of an X-ray tube assembly, showing the various components including the important aluminium filter.

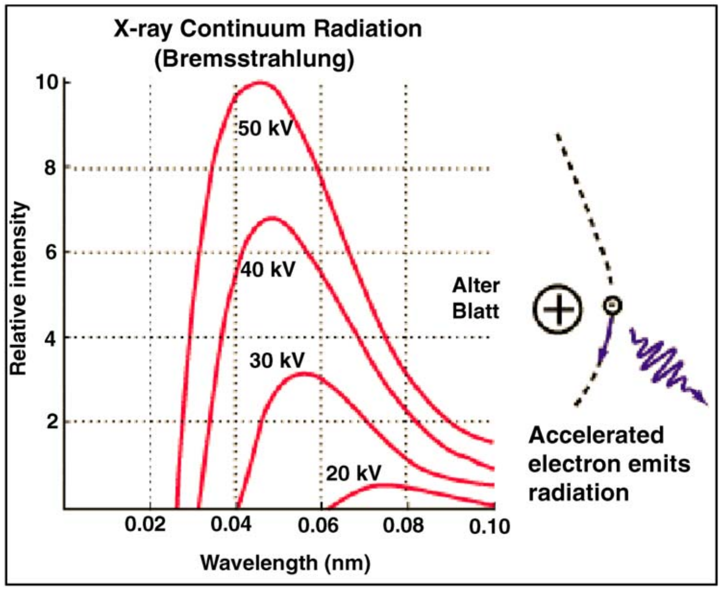

Figure 2 The bremsstrahlung continuous X-ray spectrum showing the effect of different voltages (kV).

produced. Increasing the kV increases the number of X-rays produced and their energy. The filament current controls the tube current (mA) and the number of X-rays only, without affecting their energy. The mA should be kept low and increased only if the high voltage alone cannot achieve the desired image quality. See Fig. 2.

Since X-rays are produced by the deceleration of charged particles or electrons they are in essence electromagnetic waves, similar in nature to radiowave, microwave, infrared, visible light, ultraviolet, and gamma radiations. X-rays exist in the higher energy end of the electromagnetic spectrum, which explains their high penetrating power. Therefore, just like other electromagnetic radiations, X-rays travel at the speed of light (300,000 km/s), travel in straight lines, are not affected by electric or magnetic fields, and are absorbed or scattered by matter. Most importantly, they obey the inverse square law that says that the intensity of X-rays decreases as the square of the distance from the source increases. X-rays also are invisible and have the ability to ionise atoms and molecules. It is the effects of this ionisation that ultimately damage or kill living cells.

The interaction of X-rays with matter, resulting in the ionisation of atoms and molecules, occurs in two main ways. If the X-ray hits an electron in one of the inner orbits of an atom, the X-ray is completely absorbed, and the electron is ejected from the atom, resulting in a positive–negative ion pair. This is called *photoelectric absorption*. If the X-ray hits an outer orbit electron, the electron is ejected from the atom, again resulting in an ion pair. The X-ray, however, is not absorbed, but is deflected or scattered, to continue on with lower energy. This is called *Compton scattering*. Compton scattering creates the radiation field around the patient during X-ray exposure and constitutes the radiation hazard for the surgeon and attending staff.

The quantities and units used to measure X-radiation are:

1. *Dose*—the amount of energy absorbed per unit mass of matter. The unit is the Gray (Gy) (1 J/kg).
2. *Equivalent Dose*—used to stipulate the radiobiological effect of dose as the energy absorbed per unit mass (equal numerically to dose for X-rays). The unit is the Sievert (Sv) (1 J/kg). As the Sievert is a large unit, the millisievert (mSv), one thousandth of a Sievert, is used in medicine.

The International Commission on Radiological Protection (ICRP) has a System of Radiological Protection based on three principles, first expounded in ICRP publication 26 and later refined in ICRP publication 60:[6]

1. *Justification*. No practice involving exposure to radiation should be adopted unless it produces a net benefit.
2. *Optimisation*. All exposures should be kept As Low As Reasonably Achievable (ALARA), economic and social factors being taken into account.

3. *Limitation*. The exposure of individuals should be subject to dose limits.

There are annual Dose Equivalent Limits set both for members of the public and for persons who are occupationally exposed. These limits do not include exposure to background radiation or exposures for medical purposes.

1. The annual whole body Dose Equivalent Limit for occupationally exposed persons is 20 mSv.
2. The annual whole body Dose Equivalent Limit for members of the public is 1 mSv.

Effects on living tissue

Ionising radiations interact with matter through excitation and ionisation of atoms and molecules. This causes damage by direct or indirect action.

Direct action

An X-ray track passing through a cell may directly disrupt the molecular bonds of cellular material such as DNA and cell membranes. The cell either dies or if the DNA is distorted will replicate to abnormal or cancerous cells. Damage to the DNA in the nucleus of a single cell probably represents the initial event of carcinogenesis. Low dose radiation to human fibroblasts has been shown to produce double strand DNA breaks that are irreparable.[7] A single X-ray track has the ability to irreparably damage a cell, with the possibility of deleterious effects, and this leads to the concept that the effects of exposures to X-rays, regardless of how small the dose, are cumulative over the organism's lifetime.

Indirect action

Water molecules are ionised into HO, HO_2 free radicals or hydrogen peroxide H_2O_2 that have the ability to disrupt molecular bonds. Most long term effects of radiation are caused by this process as water is the most abundant molecule in the cell.

The effects of radiation are classified as stochastic (probabilistic) or non-stochastic (deterministic).

Stochastic effects are those where the probability of an effect occurring increases as the radiation dose increases and a lower threshold of dose is thought not to exist.[8] The lack of a lower threshold is logical when it is realised that a single X-ray track may damage a cell. A latent period exists between the radiation exposure and the appearance of the effect, often of many years. The risk factor for fatal cancers induced by radiation depends on the tissue radiated and dose (thyroid cancer that has a high cure rate and cancers that may occur in old age and not be the cause of death are not included in the risk assessment). For uniform acute exposure of the whole body the probability for fatal cancer given by UNSCEAR (1988)[9] and BEIR V (1990)[10] is about 1 in 10 per Sievert .With prolonged exposure ICRP 60 (1991)[6] gives a value of 1 in 20 per Sievert for the probability of induced fatal cancer.

Non-stochastic effects are those where the severity of the effect increases with the dose and a threshold probably exists. The effects are specific to the tissue, for example, cataract formation, non-malignant skin changes, gonadal cell damage leading to impaired fertility and bone marrow dysplasia. If the dose is not greatly above the threshold the effects are temporary and reversion to normal occurs. If the dose is greatly above the threshold cell death occurs.

Background radiation

Everyone is exposed to a background radiation that is either naturally or artificially generated. The natural sources are cosmic radiation, gamma radiation from natural uranium, inhaled radon gas from the decay of uranium and radioisotopes in the diet and in our bodies. The artificial sources are medical generated X-rays and radionuclide studies and are estimated to form 15% of the total average background radiation dose to the population.[11] The effective whole body dose equivalent from natural sources is about 2.1 mSv per annum in areas of average background radiation and in some areas can rise to levels of 8–20 mSv per annum. A return air trip between Europe and Australia will incur an additional dose of about 0.28 mSv.

Diagnostic exposure

Table 1 compares the average exposures of common radiological examinations to background radiation and gives the risk of fatal cancer induction for each examination. Recent work[12] based on statistical models using the annual rate of diagnostic radiological procedures to estimate the dose to various organs and then applied to a model for radiation induced cumulative cancer risk suggests that in the USA, UK and Australia the incidence of cancers per annum induced from diagnostic radiological

Table 1 Average Exposures of some Examinations compared to Background Radiation

Diagnostic procedure	Typical effective dose (mSv)	Risk of fatal cancer per examination*	Equivalent period of natural background radiation**
X-ray examinations:			
Limbs and joints (except hip)	<0.01	1 in a few million	<1.5 days
Teeth	<0.01	1 in a few million	<1.5 days
(single bitewing)			
(panoramic)	0.01	1 in 2 million	1.2 days
Chest (single PA film)	0.02	1 in a million	2.4 days
Skull	0.07	1 in 300,000	8 days
Cervical spine (neck)	0.08	1 in 200,000	1.6 weeks
Hip	0.3	1 in 67,000	5.6 weeks
Thoracic spine	0.7	1 in 30,000	3.2 months
Pelvis	0.7	1 in 30,000	3.2 months
Abdomen	0.7	1 in 30,000	3.2 months
Lumbar spine	1.3	1 in 15,000	5.6 months
Barium swallow	1.5	1 in 13,000	6.4 months
IVU (kidneys and bladder)	2.5	1 in 8000	1 year
Barium meal	3	1 in 6700	13 months
Barium follow	3	1 in 6700	13 months
Barium enema	7	1 in 3000	2.6 years
Cholecystography	1	1 in 20,000	5 months
Cholangiography	2.6	1 in 8,000	13 months
Cardiac Catheterisation	18.9	1 in 1,000	6.8 years
CT head	2	1 in 10,000	10 months
CT cervical spine	2.6	1 in 8000	13 months
CT lumbar spine	6	1 in 3300	2.3 years
CT chest	8	1 in 2500	3 years
CT abdomen/pelvis	10	1 in 2000	3.6 years
Radionuclide studies:			
Lung ventilation (^{81}Kr^{m})	0.1	1 in 200,000	2 weeks
Lung perfusion (^{99}Tc^{m})	1	1 in 20,000	5 months
Kidney (^{99}Tc^{m})	1	1 in 20,000	5 months
Thyroid (^{99}Tc^{m})	1	1 in 20,000	5 months
Bone (^{99}Tc^{m})	4	1 in 5000	2 years
Dynamic cardiac (^{99}Tc^{m})	6	1 in 3300	2.3 years
Myocardial perfusion (^{201}Tl)	18	1 in 1100	6.7 years

*Approximate lifetime risk for patients from 16 to 69 years old: for paediatric patients multiply risks by about 2; for geriatric patients divide risks by about 5.
**Australian average about 2.6 mSv/yr: regional averages range from 1.5 to 7.5 mSv/yr.

procedures is 5695, 700 and 413, respectively. There is epidemiological evidence of increased cancer risk with whole body exposures in the range of 10–50 mSv for acute exposures and 50–100 mSv for protracted exposures.[13] Many diagnostic CT procedures would come within the former range and for many people a lifetime's cumulative diagnostic exposure would fall within the latter range. This is shown in the US Scoliosis Cohort Study[14] where adolescent females exposed to multiple diagnostic X-rays giving a mean breast dose of 108 mSv in 25 exposures have a statistically significant increased risk for breast cancer.

Although the risks are small the surgeon must justify exposing patients to ionising radiation. If the use is for a specific purpose that gives clinical benefit then that benefit outweighs the risk. If there is no potential patient benefit expected from the investigation then the risk is unacceptable and the investigation should not proceed. This concept determines that many current "follow up" X-rays are essentially for the surgical assessment of specific procedures and appliances and not for individual patient benefit. These X-rays must be considered as research investigations and the patient must be informed of the radiation risk and local research protocols followed. It must be remembered that though the risk of inducing carcinogenesis may be small, if a small risk is applied to a large population then a significant health problem could result.

Radiation protection

This falls into five areas;

a. minimisation of radiation use,
b. maximising the distance between the individual and the X-ray source, beam and scatter,
c. use of lead screens,
d. personal protective garments, and
e. monitoring personal exposure dose.

These have particular application to the surgeon using image intensification or fluoroscopy in the operating room. In this situation the supervision of the radiation protection of the patient, the staff and the surgeon is the surgeon's responsibility.

Minimising radiation use is enshrined in the ALARA principle of optimisation that radiation dose, both in ordering diagnostic X-rays and in the operating room using the fluoroscope be kept *A*s *L*ow *A*s *R*easonably *A*chievable (ALARA is the acronym). With fluoroscopy the radiation exposure is minimised by careful positioning of the patient as close as possible to the intensifier or receptor, with minimal screening time, the smallest possible field size, the use of image memory facilities and an awareness of the scatter patterns around the fluoroscope.

X-rays obey the inverse square law that the intensity of the X-rays (photons per unit area) is inversely proportional to the square of the distance from the X-ray source. This fact is vital to the understanding of radiation protection. The effect is that the exposure received at 2 m from a fluoroscope and beam is relatively minimal and it has been suggested that at distances greater than this, operating theatre staff need not wear lead gowns. However it is recommended that lead gowns be worn by all staff as even at 2 m there is some exposure and it is unreasonable to expect staff in the heat of the moment to always be thinking of their distance from a fluoroscope that may be hidden by the drapes with the direction of its beam being constantly manoeuvred by the surgeon.

Lead screens reduce exposure to scatter considerably. They may be mounted on the operating table and hang between surgeon and fluoroscope or ceiling mounted and lowered as appropriate. Mobile lead screens can be draped and placed between surgeon and beam. A mobile screen can easily be made by hanging a lead gown on the cross arm of a lowered drip stand and draping this as necessary to stand in the operating area. Surgeons should always consider the provision of lead screening with the purchase of new equipment and when consulted on operating theatre design.

Personal protective garments are a lead gown, thyroid shield and lead acrylic glasses or head shield. The gown must be "wrap around" with overlap and of 0.5 mm lead equivalence (lead equivalence is the thickness of lead that would have the same absorption properties as the thickness of any other material placed in the path of the radiation beam). Two piece garments with a bodice and skirt are more comfortable but the bodice must overlap the skirt. A thyroid shield must protect the neck. The eyes must be protected by lead acrylic glasses or head shield. These may be made to specific prescription or lead acrylic protective glasses (wrap around glasses or clipons) may be worn over prescription glasses. The thyroid shield and lead acrylic glasses may be replaced by a head shield that has a full lead acrylic visor anchored to the gown or supported by a head band. The visor also acts as a surgical splash protector but has the drawback of being relatively heavy for prolonged wear. Lead gowns must be handled carefully and not thrown down and crumpled as the protective lining will crack and be ineffective. For this reason gowns must be visibly inspected before each wearing and regularly checked by the radiology department and the date of the last check marked on the gown. These inspections should be at least annually and ideally every six months. Protective garments still allow penetration of about 10% of the radiation and even when appropriately protected the wearer should move as far as possible away from the fluoroscope and area of scatter.

All personnel exposed to radiation must wear a radiation personal dosimeter in a constant position beneath the protective gown to record any personal dose. Only in this way will one be aware of one's dose, be able to vary practice if the dose increases and be able to record a lifetime's work exposure. Ideal monitors are the optically stimulated luminescence dosimeter (OSL) and thermo-luminescent dosimeter (TLD). These must be safely stored away from radiation sources and never shared. The exposure of the patient for each operative procedure should be recorded in the operating note.

A special area of radiation protection concerns the sexually active female surgeon and nurse not observing contraceptive precautions. Ideally these females should avoid being part of the "scrub team'' when ionising radiation is in use. If this is not practical then maximum protection with a recently tested 0.5 mm lead equivalence wrap around gown is essential and it is critical to maintain the maximum distance from the X-ray source, beam and area of scatter (special 0.5 mm lead equivalence gowns are available with a 1 mm lead equivalence thickness over the foetal area). If such staff are ''unscrubbed'' in the theatre they must follow the same regime and be made aware that they must be conscious of the position of the X-ray equipment since it may be moved at any time and compromise their safety distance. Once a pregnancy has been discovered these special precautions must be continued until term. Studies of childhood cancer risks following *in utero* diagnostic exposures conclude that exposures of 10 mSv cause a significant increase in the risk of childhood cancer.[15]

Advice when operating with X-rays

Fluoroscopy is essential to orthopaedic surgical practice but the dangers of ionising radiation pose a threat to all staff within the operating room and to the patient. For the staff the danger lies in the insidious cumulative effect of low dose exposure over time. A lack of appreciation of the risks leads to practices that include excessive and inappropriate use of the fluoroscope, poor supervision of junior surgeons often with an unrealistic expectation of their skills and inadequate application of approved protection regimes. The deleterious effects of ionising radiation can be minimised over a surgical career by strict observance of the following guidelines:

a. Maximising distance from the energised fluoroscope. Moving away from the energised fluoroscope invokes the benefit of the inverse square law. Simply put, moving from 1 m from the energised fluoroscope to 2 m away reduces the intensity of the X-rays by a factor of four. The radiation exposure is greatest at the X-ray tube or generator end of the C arm and lowest behind the image receptor or intensifier. See Figs. 3–8.
b. Decreasing the number and duration of exposures reduces the radiation dose in direct proportion. Correct positioning to anatomical landmarks or surgical features minimises exposure as it eliminates the need ''to screen to search'' for the desired feature. Once the position of an anatomical landmark has been established it can be marked on the drapes to give future accurate positioning of the fluoroscope.
c. Correct positioning of the fluoroscope is critical in minimising exposure of the surgeon both from the beam and scatter. It must be constantly remembered that the exposure is greater on the X-ray generator side of the fluoroscope than on the receptor or image intensification side of the fluoroscope. Positioning the image receptor as close as possible to the patient and the X-ray tube as far away as possible reduces primary radiation exposure of the patient and scatter to the surgeon. If more X-rays are needed for better image quality it is important to increase the kV rather than the mA. Increasing the kV increases the energy as well as the intensity of the X-rays allowing more X-rays to reach the receptor. This applies in lateral views of the femoral neck and trochanters when the patient must be on the edge of the operating table or even overhanging the edge to allow the image receptor to be close to the lateral aspect of the patient's hip.
   A lead shield suspended from the operating table or ceiling or a mobile shield between surgeon and table gives a further significant reduction in the surgeon's exposure to scatter. See Fig. 5. A mobile shield can be easily made by hanging a lead gown on the cross arm of a lowered drip stand. It may be sterile draped if appropriate.
   If the C arm is angled 15–20° with the receptor towards the surgeon the scatter to the surgeon's head and neck is reduced but the scatter to the assistant on the opposite side is increased and the surgeon and assistant must recognise this and the assistant move away. If the C arm is angled with the image receptor away from the surgeon the scatter to the surgeon increases. See Figs. 6 and 7.
d. The utilisation of image intensifier memory and image storage facilities in preference to further exposures reduces radiation dose.
e. The fluoroscope must not be used as a convenience or expediency over the use of standard X-ray equipment.
f. Intramedullary locked nailing systems are often associated with multiple and long exposures. If marked difficulty is encountered in introducing guide wires it is acceptable and wise to proceed to an open procedure rather than persist with closed manipulation and expose patient and staff to further radiation exposure.
g. With locked nailing systems radiation dose can be reduced by using only one cross locking screw if stability is not compromised.

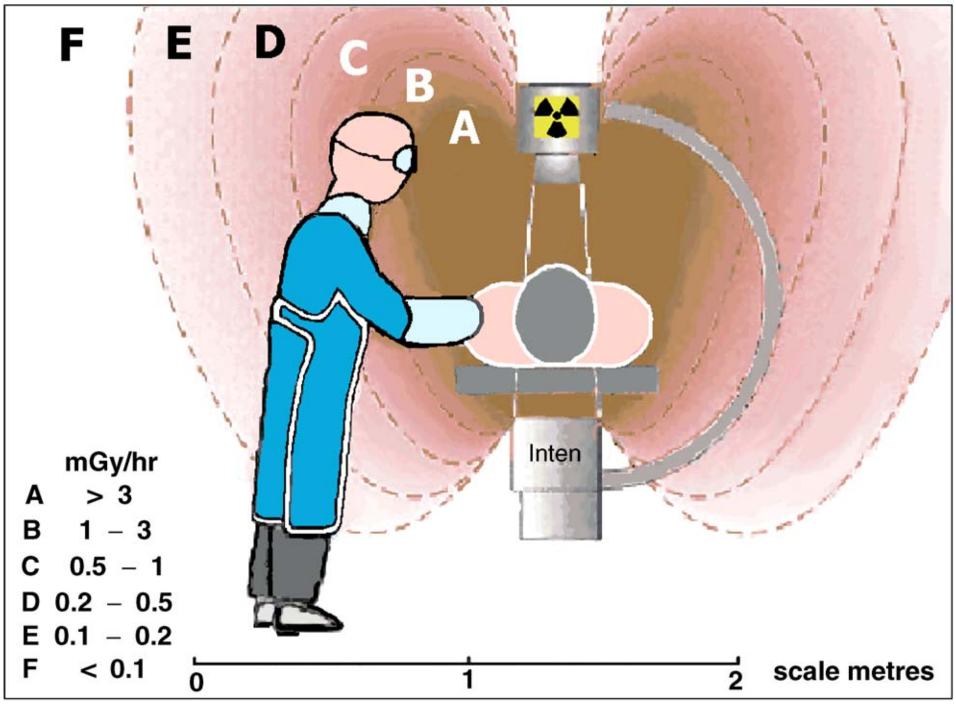

Figure 3 With the X-ray generator above the table the maximal scatter is towards the surgeon's head and neck. Note that the scatter at the generator end of the C arm exceeds that at the receptor end. Compare with Fig. 4.

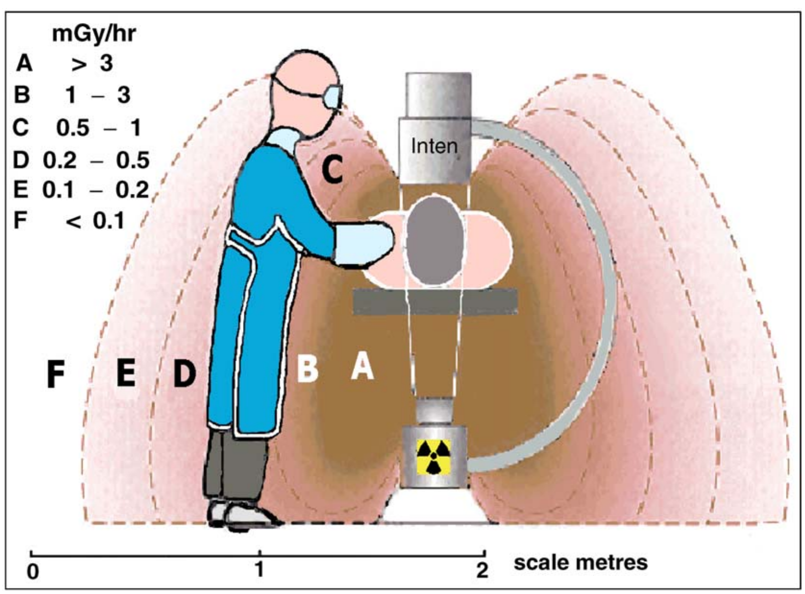

Figure 4 With the X-ray generator beneath the operating table the receptor can be placed closer to the patient so reducing the primary radiation exposure to the patient. The scatter towards the surgeon's head and neck is significantly reduced. Compare with Fig. 3.

h. Positioning the patient with airbags rather than water bags will reduce dose and scatter.
i. Junior surgeons must be given senior assistance with difficult fractures, as there is evidence that in these situations the unsupervised and inexperienced surgeon uses excessive exposures.[16] The same problem occurs with junior radiographers and the surgeon should ask for senior radiographer supervision when operating on complex fracture patterns such as three and

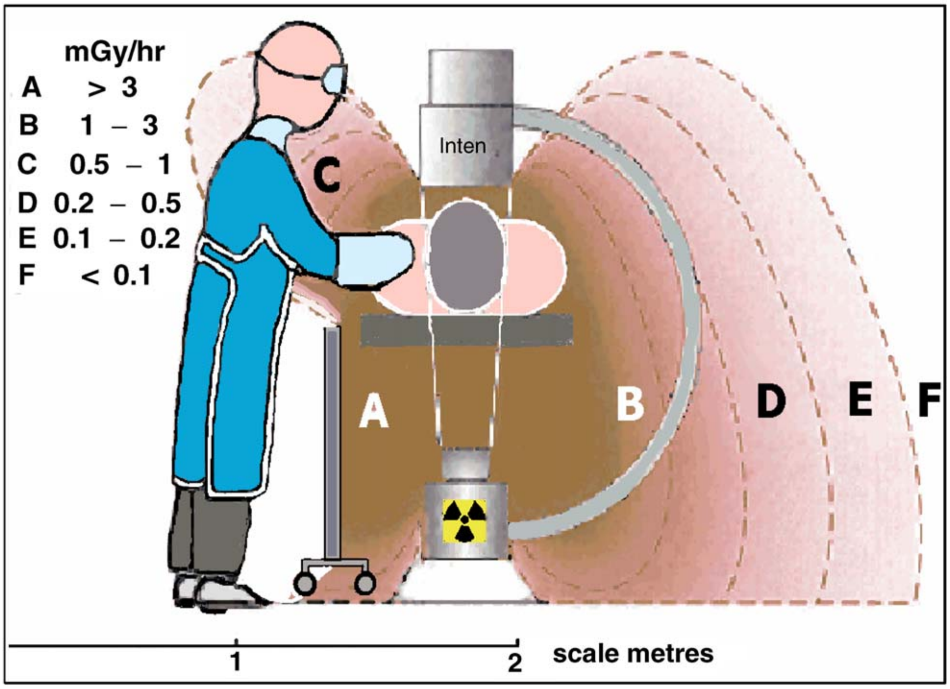

Figure 5 With the receptor close to the patient and with a mobile or table suspended shield the scatter is significantly reduced towards the surgeon. Compare with Figs. 3 and 4.

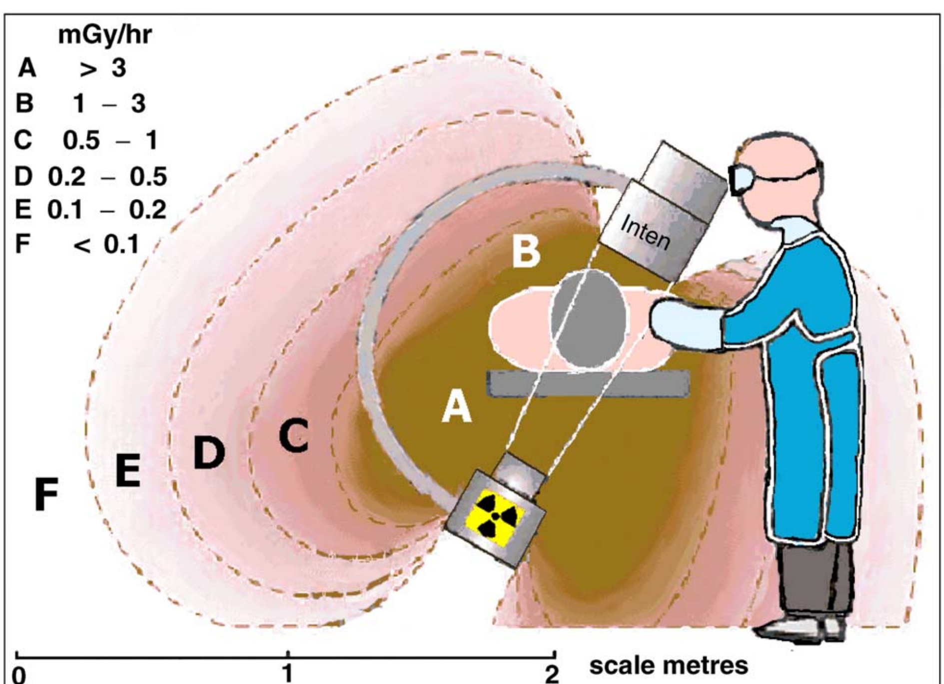

Figure 6 With the C arm angled 20 degrees with the image receptor towards the surgeon and adjacent to the patient the scatter to the surgeon's head and neck is reduced. A table suspended or mobile screen would reduce the scatter to minimal levels (see Fig. 5). The scatter to the assistant on the opposite side of the table is increased and the assistant must move away during exposures.

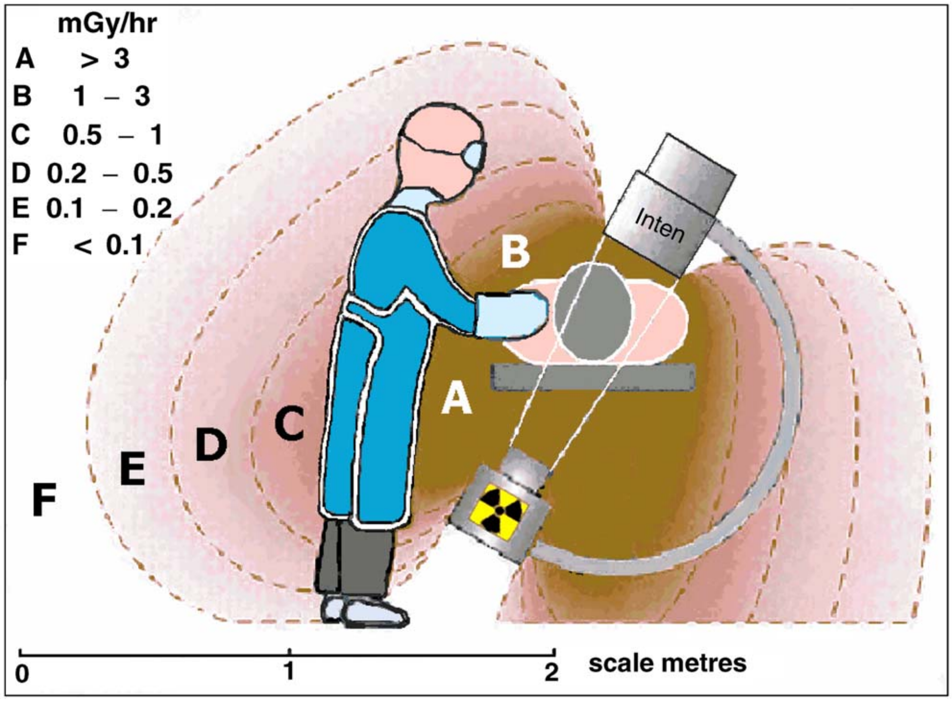

Figure 7 With the C arm angled 15 degrees with the image receptor away from the surgeon the scatter to the surgeon's head and neck increases. The position of the generator interferes with the use of a rigid table suspended or mobile screen. The scatter to an assistant on the opposite side decreases but the assistant must utilise full protection methods.

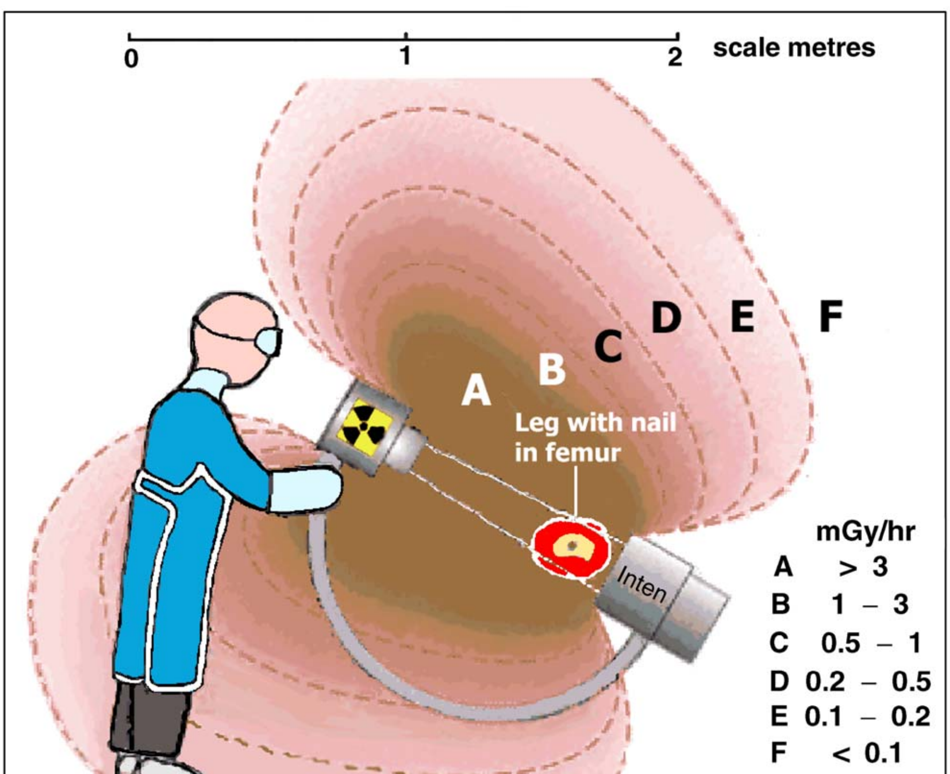

Figure 8 The C arm is positioned to allow the surgeon operative access to the lower limb to insert cross screws to the lower femur or tibia. The closeness of the receptor to the limb and the small volume of tissue minimises radiation dose and back scatter. With real time operative manoeuvring the surgeon must avoid the X-ray beam and use long surgical instruments. A mobile screen in front of the surgeon greatly reduces scatter towards the surgeon (see Fig. 5).

four part trochanteric or segmental femoral fractures.

j. Constant use of high quality and properly maintained protection equipment, both personal and fixed table or ceiling mounted screens.
k. The fluoroscope must never be used inappropriately such as when proudly displaying an anatomically fixed fracture, in real time, to the theatre staff or students.
l. The receptor must not be used as an operating table. The radiation exposure is unacceptable and there is the risk of explosion should the fragile receptor be inadvertently punctured by a drill or other instrument.
m. Constant supervision of radiation practices by senior surgeons and inclusion of ionising radiation and its hazards in the continuing education process.

Cross screwing the lower femur and tibia are scenarios where it is necessary to reverse the C arm and have the X-ray generator on the surgeon's side and the receptor close to the patient on the opposite side of the limb to allow surgical access to the limb. As the volume of tissue being X-rayed in these cases is relatively small, the back scatter to the surgeon is diminished compared to the torso or hip but the surgeon should stand back during exposures and if it is necessary to have real time operative exposures the surgeon must use the longest possible instruments. Radiation protective gloves are useful in this instance. See Fig. 8.

Code of conduct

As ionising radiation is dangerous and can induce cancer every surgeon must have a personal code of conduct for the safe use of the modality. This should encompass recognition of the dangers of radiation, compliance with protection procedures, ensuring staff and patient safety, continuing education and fulfilling all legislated regulations.

Regulations

It is beyond the scope of this paper to list the ionising radiation regulations enacted in every country where this paper may be read. Suffice it to say that all surgeons using ionising radiation must be aware of the statutory regulations applicable to their workplace and conform to protection procedures. Ideally professional Orthopaedic Associations should promulgate the local regulations and protection procedures to their members together with a code of conduct governing ionising radiation use.

Practice hints

- X-rays can have deleterious effects
- Effects of X-rays have no known safe lower threshold of dose
- Always wear a lead gown, thyroid shield, lead acrylic glasses and a personal dosimeter in the presence of ionising radiation
- Use lead or lead acrylic shields and barriers whenever possible
- Remember the inverse square law and maximise your distance from X-ray generators, beam and scatter
- Always practice the ALARA principle

Research directions

- Non-ionising alternatives for cross screwing

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