INTERNATIONAL ATOMIC ENERGY AGENCY
UNITED NATIONS EDUCATIONAL, SCIENTIFIC AND CULTURAL ORGANIZATION
INTERNATIONAL CENTRE FOR THEORETICAL PHYSICS
I.C.T.P., P.O. BOX 586, 34100 TRIESTE, ITALY, CABLE: CENTRATOM TRIESTE

H4-SMR 471/10

COLLEGE ON MEDICAL PHYSICS

10 - 28 SEPTEMBER 1990

PRINCIPLES OF RADIATION PROTECTION

P. Griffith

County Hospital
Lincoln
UK

INTRODUCTION

Radiation protection is concerned with the protection of people, both individually and in general, against detrimental effects of exposure to radiation, while still allowing necessary activities from which radiation exposure may arise.

Radiation is part of man's natural environment through cosmic rays, radioactivity in rocks and in radioactivity within our bodies. These natural sources of ionising radiation constitute a lower limit to the radiation doses received by the population at large and radiation protection procedures can do little or nothing to reduce this limit. It is therefore apparent that our environment is, and always has been, relatively safe from the effects of such radiations otherwise there would be ample evidence to the contrary. It follows that one of the basic tasks of radiation protection is to establish the levels of risk to the population due to natural or background radiation and also to the man-made sources of radiation. Once the level of risk has been ascertained, appropriate maximum radiation dose levels may be set whose associated risk is not greater and frequently much less than the risks experienced from other aspects in life, eg risk of accidents, contracting a fatal disease etc.

The recognition of the potentially harmful effects of radiation led to the creation in 1928 of the International Commission on Radiological Protection - ICRP. This body maintains a watching brief on all aspects of protection against ionising radiation and makes recommendations concerning basic principles and radiation dose limits. ICRP makes recommendations only and it is the responsibility of governments of individual countries to implement those recommendations which they consider appropriate to their own national circumstances.

Much of the philosophy and all the concepts in this course emanate from the current thinking of ICRP contained in various ICRP Publications. The three important general principles are:

1. Every practice resulting in an exposure to ionising radiation shall be justified by the advantages it produces - JUSTIFICATION.

2. All exposures shall be kept as low as reasonably achievable - OPTIMISATION.

3. The sum of the doses and committed doses received shall not exceed certain limits - DOSE LIMITATION.

It is important to appreciate that Radiation Protection is not concerned with merely observing dose limits. There is now great emphasis being placed on the idea that any exposure should be justified by some benefit and that exposures should be kept As Low as Reasonably Achievable, economic and social factors being taken into account. This is known as the ALARA principle.

Radiation protection embraces many subjects including radiobiology, genetics, statistical analysis of risk, radiation physics etc. In the brief time available it is hoped that enough of the basic science and concepts can be covered in order to appreciate the current thinking in the subject, supplemented, wherever possible, with practical examples.

PHYSICAL CONCEPTS

Interaction of X and Gamma rays with Matter

The interactions of X and gamma rays with matter may be divided into three main categories depending on the energy of the photon. These three mechanisms are the Photoelectric Effect, Compton Scattering and Pair Production. All result in the energy of the photon being transferred to electrons which subsequently lose energy by further interactions.

Photoelectric Effect

In the Photoelectric effect all the energy of the photon is transferred to an inner shell electron which is ejected from the atom. Restoration of the vacancy results in the production of characteristic radiation in high Z materials and Auger electronics in low Z materials. As a consequence, in low Z materials all the energy of the photon is absorbed in the material.

The probability of photoelectric absorption depends upon the energy of the incident photon and the atomic number of the absorbing material.

$$\frac{\tau}{\rho} \propto \frac{Z^3}{E^3}$$

where τ/ρ is the mass attenuation coefficient for the photoelectric process.

Compton Scattering

In the Compton process the photon interacts with an outer shell electron (virtually free, in energy terms) resulting in the electron receiving some energy and being emitted at an angle whilst the photon, with reduced energy, is scattered at an angle It can be shown that

$$E = h\nu_0 \frac{\alpha(1-\cos\phi)}{1+\alpha(1-\cos\phi)}$$

$$h\nu' = h\nu_0 \frac{1}{1+\alpha(1-\cos\phi)}$$

$$\cot\theta = (1+\alpha)\tan\frac{\phi}{2}$$

where $h\nu_0$, $h\nu'$ and E are the energies of the incident photon. Scattered photon and electron respectively in MeV and $\alpha = \frac{h\nu_0}{0.511}$

These equations allow some useful conclusions to be drawn eg

a) For low energy photons only a proportion of energy is transferred to the electron, the scattered photons having approximately the same energy as the original ones.

b) At higher photon energies a much larger proportion of energy is transferred to the electron, ie the process leads to higher absorption of energy.

c) At high photon energies the radiation scattered at 90 degrees and 180 degrees is independent of incident energy and has maximum values of 0.511 MeV and 0.255 MeV respectively.

The Compton effect decreases with increasing photon energy and depends only on the number of electrons present in the volume. However, electron density is almost independent of Z and hence , the mass attenuation coefficient for the Compton effect, is nearly the same for all materials. , the linear Compton attenuation coefficient is therefore proportional to the density of the irradiated material.

Pair Production

If the energy of the incident photon is greater than 1.022 MeV the photon may interact with the electromagnetic field of the atomic nucleus to produce a negative and positive electron pair, transferring all its energy in the process. Eventual disappearance of the positron, through interaction with a free electron, results in the production of 2 photons each 0.511 MeV in energy, in opposite directions, known as Annihilation Radiation. The probability of pair production increases with photon energy above 1.022 MeV and increases rapidly with atomic number.

$$\frac{K}{\rho} \propto \frac{Z^2}{\log E}$$

Attenuation Coefficients

The total mass attentuation coefficient is the sum of the coefficients of the three main processes

$$\frac{\mu}{\rho} = \frac{\tau}{\rho} + \frac{\sigma}{\rho} + \frac{\kappa}{\rho}$$

In low Z materials such as water and tissue the Compton effect is the most important interaction for photons above 50 keV up to several MeV whilst in high Z materials such as lead (Z = 82) the photoelectric effect is important up to 500 keV. The combination of high Z and high density (11.3 g cm^{-3}) results in lead being an excellent material for radiation protection purposes in diagnostic radiology and nuclear medicine departments.

Transmission

If the intensity (I) of a narrow beam of monoenergetic photons is measured firstly without an absorber present (I_o) and then after passing through different thicknesses (x) of an attenuator it is found that

$$I = I_o e^{-\mu x}$$

ie a logarithmic plot of tranmission (I/I_o) versus x is linear. For broad heterogeneous beams this simple relationship does not apply and transmission data has been experimentally determined. Although a non linear relationship is found initially, beyond certain thicknesses of material the curves become linear.

Charged Particle Interactions

All charged particles (electrons, protons, alpha particles and nuclei) lose kinetic energy mainly through interactions between the electric field of the particle and that of the electrons in the material through which the particle is travelling. The energy transferred to the medium is inversely proportional to the kinetic energy of the particle and to the square of the distance between the particle and the electron. Thus a particle with high velocity, will be in the region of the electron only a short time and so little energy is transferred, whilst those encounters at close distances will involve large energy transfers compared to more distant encounters.

Electrons differ from other charged particles slightly because of their relatively small mass. Whereas a large particle is hardly deflected from its original path in an interaction with an electron, an electron-electron interaction can result in quite high energy losses and marked changes in direction of the incident electron. In addition electrons, because of their small mass, may interact with the electric field of the nuclei which at higher energies results in inelastic scattering and the production of x-rays.

The consequence of the interaction of charged particles with orbital electrons is the formation of ions or excited molecules. The number of ion pairs formed per unit length of track - the specific ionisation or ionisation density - depends upon the mass and charge of the particle and on the absorbing material. An alpha particle because of its large mass, causes dense ionisation along a linear track whilst an electron will undergo fewer interactions and follow a much more tortuous path.

The average energy required to form an ion pair is about 34 eV. The energy deposited per unit length of track - the Linear Energy Transfer, LET, - is related to the amount of biological damage

caused. A 1 MeV electron will create about 7000 ions/mm at the start of its track and its LET will be 0.25 keV/um. By comparison a 100 keV electron will produce 12,000 ions/mm and has an LET of 0.4 keV/um. Alpha particles can deposit energy at rates up to 200 keV/um.

Quantities and Units

Absorbed Dose

The Absorbed Dose in a medium in the ratio E/M where E is the energy absorbed by the medium due to a beam of ionising radiation is a small mass, m.

The unit of absorbed dose is the gray (Gy) where 1 gray = 1 joule per kg.

This replaces the old unit, the rad. 1 gray = 100 rads.

Kerma

However not all the energy released in the medium through the initial processes of interaction need necessarily be absorbed in the medium. The initial transfer of energy in a small volume is called the kerma (Kinetic Energy Released per unit Mass). Kerma is also measured in joules per kilogram but may differ significantly from the absorbed dose at any particular point in the medium. Air kerma values are now being used to specify the quantity of radiation in the presence or absence of an absorber and so are replacing Roentgens. An air kerma of 1 Gy represents a transfer of 1 joule of energy from the photon beam to air per kg of air. An exposure of 1 Roentgen corresponds to air kerma of 8.7 mGy.

Dose Equivalent

In radiation protection the situation is further complicated because a dose one type of radiation may produce a much larger biological effect than the same dose of a different type of radiation. It is necessary to be able to assess the risk of injury from exposure to different types of radiation and to have a unit of radiation dose for which the risk of injury or the detriment to health can be regarded as similar for all types of radiation exposure. This concept led to the concept of Dose Equivalent measured in seiverts, Sv.

The Dose Equivalent (H) at any point in a tissue is given by $H = D\ Q\ N$, where D is the absorbed dose in Gy, Q is the quality factor for the radiation and N is the product of all other modifying factors.

The values of Q are conservative, being somewhat arbitarily chosen. They are based on a range of RBE's (relative biological effectiveness) related to the LET of the radiation but are independent of the organ or tissue or the biological end-point under consideration. Thus, although Q encompasses RBE, it does not replace RBE or LET and its use is restricted to radiation protection purposes only.

For X & gamma radiation Q has a value of 1. For internal exposure to electrons of energy less than 30 keV Q has a value of 1.7 whilst for particles the value varies between 10 and 20.

At present N has been ascribed the value of 1.

BIOLOGICAL CONCEPTS

The effects of radiation exposure on cells can be of two types - Stochastic and Non-stochastic.

Stochastic Effects

A stochastic effect is one which occurs as a result of the laws of probability. For radiation induced effects the probability of a stochastic effect occurring depends upon the radiation dose received. Under such circumstances there is no such thing as a safe or threshold dose, the probability of occurrence reducing linearly down to zero dose. However the severity of the effect is independent of dose.

The two important stochastic effects are the induction of cancer in its various forms in the irradiated individual (somatic effects) and genetic effects, ie the changes in future generations. However as the radiation dose increases even though, for example, the probability of cancer induction increases, the severity of the cancer is the same.

Non-Stochastic Effects

Non-stochastic effects have a threshold value below which there is no effect but above which the severity of the effect depends upon the dose received. A good example is a cataract in the lens of the eye. Evidence suggests that these do not occur at low doses of radiation but can suddenly develop at higher doses above a certain threshold.

All Codes of Practice for Radiation Protection are now aimed at introducing conditions whereby doses of ionising radiation can be maintained at acceptable levels, considerably lower than the threshold level for non-stochastic effects and where the probability of the occurrence of stochastic effects is extremely low.

Induction of Radiation Injury

The induction of biological damage can be considered to occur in 4 stages, three of which are extremely rapid involving molecular changes, and the fourth is slower since it is the expression of these molecular changes into functional and structural changes in the cells and in the whole organism. Since water is a primary component of cells, the radiolysis of water is the important initiation of biological damage.

1st Stage - Physical - 10^{-16} sec.

Interaction and excitation as a result of energy deposition processes

$$H_2O \xrightarrow{\sim\sim} H_2O^+ + e^-$$

2nd Stage - Physico-Chemical - 10^{-6}

Formation of Free Radicals

$$H_2O^+ \longrightarrow H^+ + OH^-$$
$$H_2O + e^- \longrightarrow H_2O^-$$
$$H_2O^- \longrightarrow H^- + OH^-$$

3rd Stage - Chemical - secs.

Interaction of free radicals with organic molecules of cells, eg DNA, proteins.

4th Stage - Biological - hours/years

Transformation of chemical changes into cellular ones, eg cell death, prevention of mitosis, production of genetic defects.

Estimation of Risk

ICRP 26 places great emphasis on the concept of risk, particularly from induced cancers, with 100 deaths/million man years (1×10^{-4}) being taken as a reasonable risk figure. This compares favourably with the risk of a fatal accident in other safer industries whilst in some industries, such as mining, risks are greater by a factor of 10.

The major stochastic risks (of death not of tumour induction) have been estimated to be for the following organs:

Organ	Risk/Sv
Gonad	4.0×10^{-3}
Breast	2.5×10^{-3}
Red Bone Marrow	2.0×10^{-3}
Lung	2.0×10^{-3}
Thyroid	0.5×10^{-3}
Bone	0.5×10^{-3}
Remainder	5.0×10^{-3}
Total	16.5×10^{-3}

Thus, since about 50% of breast cancer is curable, the risk of cancer induction by radiation is approximately 5.0×10^{-3}. ($2 \times 2.5 \times 10^{-3}$). For thyroid cancer the risk of induction is much higher, $30 \times 0.5 \times 10^{-3}$ because approximately 97% of thyroid cancers can be cured. For leukaemia, lung and bone cancers the cure rate is small and therefore the risk of induction is essentially the same as the risk of death.

Prior to ICRP 26, there was major concern with hereditary effects and although the emphasis has changed to the risks of cancer in the individual, hereditary effects still comprise approximately 25% of the total risk, through irradiation to the gonads.

The figures presented are at best only approximate since there are a variety of factors which influence the induction of cancer, eg age, sex, type of radiation etc. However for lack of a better approach they are extremely valuable in presenting the risks so as to allow comparisons to be made and for radiation protection purposes. For over 20 years the maximum permissible dose for radiation workers has been limited to 50 mSv/y. However in reality, the arithmetic mean of those doses received by these workers is less than 5 mSv/y, with very few cases approaching 50 mSv. Thus the average radiation worker is exposed to a risk of $16.5 \times 10^{-3} \times 5 \times 10^{-3}$ 10^{-4} per year, and is as safe as those working in safe industries. In addition, the risks have a long latent period before death occurs, whilst fatal accidents in other industries mostly occur nearly instantly. Thus the figures tend to overestimate the risks.

The fatal risk of 10^{-4} can also be put into the following risks of everyday life.

Travelling	6,000 miles by car
Smoking	75 cigarettes
Living	1.4 days for a man aged 60

Partial Exposure

The risk from only one organ receiving a radiation dose is less than the risk should the whole body have received the same dose. Thus the risk from an absorbed dose of 1 Sv to the thyroid is only 0.5×10^{-3} compared to 16.5×10^{-3} for the same dose to the whole body. This leads to a series of weighting factors for each of the organs.

Organ	Weighting factor
Gonad	0.25
Breast	0.15
Red Bone Marrow	0.12
Lung	0.12
Thyroid	0.03
Bone	0.03
Remainder	0.3
Total	1.0

These weighting factors are valuable in assessing risk in cases of partial or non-uniform exposure and allowing comparisons to be made to whole body exposures. This approach replaces the concept of critical organ used in previous ICRP reports.

DOSE EQUIVALENT LIMITS

The ICRP states that the dose equivalent limit for radiation workers should be 50 mSv/year, ie approximately 50 times the average background radiation dose. In setting this limit, the effect of natural background radiation and radiation from medical investigations is not included, since the former cannot be controlled and the latter is assumed to carry far greater benefit than risk. They therefore fall outside the general calculation of risk/benefit.

Effective Dose Equivalent

In cases of partial exposure ICRP 26 introduced the concept of effective dose equivalent in order to take account of the fact that organs show different sensitivities to radiation. Using the weighting factors for each organ given previously the dose to that organ can be converted into the whole body dose equivalent - called the effective dose equivalent - which carries the same risk. In addition a derived limited for each of the organs is possible by dividing the whole body dose equivalent limit of 50 mSv by the appropriate weighting factor.

Thus for the gonads the dose equivalent limit is 50/0.25 = 200 mSv/year, whilst for the thyroid it is 50/0.03 = 1666 mSv/year. However ICRP feel that at no time should the dose equivalent for any organ exceed 500 mSv/year in order that non-stochastic effects be limited. This leads to the following dose equivalent limits for the various organs

Organ	Dose Equivalent Limit mSv/year
Gonad	200
Breast	330
Red Bone Marrow	400
Lung	400
Thyroid	500
Bone	500
Remainder	500

Because of the particular sensitivity of the lens of the eye to cataract formation the dose equivalent limit for the lens is limited to 150 mSv/year.

In applying these dose limits to practical situations, both the stochastic and non-stochastic limits must be considered and either one may prove to be the limiting dose. For example, if only the thyroid gland is likely to be irradiated the overriding dose limit will be the non-stochastic one of 500 mSv since this is smaller than the dose limit derived from the stochastic risk of 1666 mSv.

Committed Dose Equivalent

Where a radiation dose has been received from the intake of radioactive material, ICRP use the concept of committed dose equivalent. Calculation of this involves the physical and biological half lives of the material, quality factors, organ distribution etc. The committed dose equivalent is a quantitative assessment of the effect of a particular intake of radioactivity over the whole of a person's working life and is defined therefore on the dose accruing over a period of 50 years following intake.

Doses to Other People

Finally, besides those adults working with radiation, there is concern for the safety of young trainees in the radiation field and for those workers or any other person not involved with radiation. The dose limits for trainees are 3/10 of those of the adult employees, whilst for any other person they are limited to 1/10. The whole body dose limits are expressed in effective dose equivalent units, EDE (including the contribution of the committed effective dose equivalent, CEDE) whereas the dose limit to individual organs are in dose equivalent limits.

Category	EDE + CEDE for Whole Body		DE + CDE Annual	
	Annual mSv	Quarter mSv	Organ mSv	Lens of Eye mSv
Employers > 18 years old	50	30	500	150
Employees < 18 years old	15	9	150	45
Any other persons	5	3	60	15

DESIGNATION OF WORKERS

In the UK if an employee is "likely to receive a dose of ionising radiation which exceeds three tenths of any relevant dose limit" then that person must be designated as a classified person. Such a person must be subject to medical surveillance with periodic reviews of health at least every 12 months, the records of which must be kept for at least 50 years. In addition, the employer must also arrange for the dose which the classified person receives to be measured regularly and again for the records to be kept for at least 50 years.

However this does not mean that persons who are not classified should not have dose records and medical records. There is simply no legal requirement to do so. In reality, regular monitoring of those who are not classified is the best way to justify the lack of designation of personnel.

Any employee, whether classified or not, whose annual dose exceeds 3/10 of the limit for employees shall be subject to an investigation to see if the working practices involved are in keeping with the ALARA principle or whether improvements can be made which would lead to lower doses. Records of any such investigations must be kept for at least 2 years.

In the medical field it is unlikely that any of the groups of staff working with radiation need to be classified, although radiological monitoring of their received doses and of their environment should be carried out as a precaution.

Personnel Monitoring

Regular monitoring of the radiation doses received by personnel is not only important for the individual's point of view but also may yield important information on procedures adopted by that individual in everyday practice. The main method by which personnel monitoring has been carried out hitherto is by the use of film badges. These incorporate plastic, tin and aluminium filters so as to allow the type of radiation to be distinguished. Unfortunately photographic film cannot be re-used and the data obtained is necessarily retrospective and may be difficult to relate to the event which caused it.

An alternative approach using thermoluminescent dosemeters obviates many of the disadvantages of the film badges. Among the advantages are the availability of specialised dosemeters, eg for finger doses, and the fact that the technique lends itself to computerisation. However the information gained is still retrospective.

When a prompt measurement of dose is required, pocket dosemeters are available, usually based on small GM tubes. When the dose rate exceeds some pre-set value a warning noise is emitted and wearer is able to take prompt action. The more expensive models also record the dose received and display it in a digital form.

WORKING AREAS

In the UK employees and members of the public are protected from unnecessary exposure to radiation by clearly designating working areas where ionising radiation is being used. A distinction is made between two types of area - controlled and supervised.

A controlled area is where the instantaneous dose rate (averaged over 1 minute) exceeds 7.5 uSv/hour and where an adult employee is likely to receive more than 3/10 of any relevant dose limit (eg 15 mSv whole body dose/annum). Access to a controlled area is restricted to classified personnel or to other people working under a written scheme of work or to patients undergoing therapy or diagnostic procedures.

A supervised area is one in which a person is likely to receive in excess of 1/3rd the value required for designation of a controlled area (eg 5 mSv whole body dose/annum). Access to supervised areas, eg waiting rooms in nuclear medicine departments, should be restricted to those people whose presence is necessary.

Design of Therapy and Diagnostic X-ray Rooms

In order to reduce the dose rate to an acceptable level at the position occupied by personnel, it is usually necessary to place protective barriers between them and the radiation source.

Three types of radiation from the source must be considered - primary, leakage and scattered.

Primary - this is the radiation which emerges from the collimating system, confined to a cone, the size of which is determined by the maximum field size of the unit. This cone can be rotated within a vertical plane.

Leakage - this is radiation which emerges from the head through the protective barrier. This should be limited by the protection around the head to 0.1% of the useful beam at 1m.

Scatter - the main source of scatter will be the patient but scatter will also occur from other objects as well as the walls of the room. For most situations it can be assumed that for large field sizes the scattered radiation at 90°, 1m from the scatterer is 0.1% of the primary beam at the scatterer.

Typical Calculation

Linear accelerator to be installed in a room so that the external areas can be unsupervised.

For unsupervised areas — Dose Rate < 2.5 uSv/hr.

Since area can be occupied up to 8 hours — Total Dose = 8 x 2.5 = 20 uSv.

"Beam-on" time for Linac only 2 hrs within 8 hour period — Dose Rate $\leq \frac{20}{2}$ = 10 uSv/hr.

Linac spends only 20% of time pointing laterally — Instantaneous Dose Rate $\leq \frac{10}{0.2}$ = 50 uSv/hr.

Primary Beam

Output of linac at 1m — Dose Rate = 240 Sv/hr.

At 5m — Dose Rate = $\frac{240}{5^2}$ = 9.6 Sv/hr.

Therefore Transmission Required = $\frac{50 \times 10^{-6}}{9.6} \simeq 5 \times 10^{-6}$

From Transmission Curves

For 6 Mv this requires 190 cm concrete

For 10 Mv this requires 220 cm concrete

Leakage Radiation

Primary beam at 1m — Dose Rate = 240 Sv/hr.

Leakage Radiation (0.1%) — Dose Rate = 0.24 Sv/hr.

Closest Proximity of head to wall = 2.5m.

Leakage Radiation at 2.5m — Dose Rate = $\frac{240}{2.5^{-2}}$ = 38 mSv/hr.

Transmission required = $\frac{10 \times 10^{-6}}{38 \times 10^{-3}} = 2.6 \times 10^{-4}$

This requires 120 cm of concrete at 6 Mv.

Scatter Radiation

Often since scattered radiation is less than 0.1% of primary beam and is of lower energy, then if the walls and ceilings can cope with leakage radiation, scatter should not be a major problem except in the entrance mazes.

Materials used

By far the most useful material for protection purposes in modern building design is mass concrete or concrete block-out. For diagnostic facilities thicknesses vary between 10 and 30 cm. but this can be reduced, where space is at a premium (but at extra cost) by the use of high density concrete made out of barium ore or iron ore aggregates. For therapy rooms thicknesses of between 1 and 2.5 meters are common. The quality of any concrete used is of great significance to the protection afforded and it is essential that the mix is vibrated thoroughly to remove any air cavities.

Frequently in radiation protection the level of protection is expressed in terms of lead equivalent. This is the thickness of lead which provides the same level of protection as the barrier concerned. The lead equivalent of a material varies considerably with incident energy due to the different contributions of the Compton and Photoelectric effects. In diagnostic departments and radioisotope departments lead has widespread application in the construction of doors, screens and aprons, as well as on walls or floors if load-bearing or space available are important considerations.

RADIATION DOSES TO PATIENTS

Although the benefits of medical uses of ionising radiation far outweigh the risks, the fundamental principles of radiation protection i.e. justification and optiumisation are as important when considering radiation exposure of patients as they are in any other aspect of this field. In the U.K. it is now a legal requirement that the equipment used in diagnostic radiology produce a medical exposure with minimum practical dose to the patient and that the procedures are selected which will achieve the lowest patient doses.

Measurement of patient doses also provides essential information about radiographic facilities and technique, clearly demonstrating where improvements are possible. This is important in implementing the ALARA principle. Any reduction in patient dose has the additional benefit of reducing the dose to those staff working with the patients.

A recent publication of the National Radiation Protection Board in the U.K. shows that ten X-ray examinations account for 88% of the contribution to the somatic dose of the population. These are:

Examinations	Contribution to Somatic Dose %
I.V.U.	20
Lumbar Spine	19
Barium Meal	12
Chest	7
Skull	7
Barium Enema	6
Abdomen	5
Thoracic Spine	5
Cholecystography	4
Pelvis	3
Total	88

Thus even though there is relatively low radiation dose from a standard chest X-ray, the examination features high on the list because of its widespread usage and hence its significant contribution to population dose.

The entrance doses for different X-ray procedures vary considerably but of much greater concern is the variation between one hospital and another. In the NRPB survey the middle 80% of results show a variation of 5:1 but between the best and the worst there is a staggering variation of 100:1. Infact the lowest dose recorded by the worst hospital is larger than the greatest dose recorded by the best hospital.

In addition the records of the number of films taken and the screening times used for different investigations clearly show the variation in technique even allowing for the variation in patients.

EXAMINATION	MEAN ENTRANCE DOSE mSv	MINIMUM mSv	MAXIMUM mSv	MAX/MIN
Barium Enema	7.7	2.9	33.6	12
I.V.U.	4.4	1.4	35.1	25
Barium Meal	3.8	0.6	24.4	41
Cholangiography	2.6	0.4	9.1	20
Lumbar Spine	2.2	0.4	7.4	20
Abdomen	1.4	0.1	9.9	84
Chest	0.05	0.002	1.3	460

	NO. OF FILMS MEAN	NO. OF FILMS MAX/MIN	SCREENING TIME MAX/MIN
Barium Enema	8.5	17	810:49 sec
I.V.U.	8.2	7	
Barium Meal	7.8	42	1059:46
Cholangiography	7.8	7	714:36
Lumbar Spine	3.4	7	
Abdomen	1.4	4	
Chest	1.3	4	

Factors which affect Patient Dose

a) Sensitivity of the Detector

Modern intensifying screens result in an enormous reduction to patient dose. For many years there was a trade off between sensitivity and resolution but this has largely disappeared with the present generation of rare earth screens.

b) Material between the Patient and film

This includes many necessary structures such as Couch top, Cassette anitscatter grid etc. These structures should be as transparent as possible to X-rays in order to miniumise the exposure. This aluminium was standard for many years but now carbon fibre offers worthwhile advantages. Recent calculations using Cost Benefit Analysis (CBA) show that the investment to re-equip the Health Service in the U.K. with carbon fibre materials would repay many times over in terms of lower health detriment.

c) Tube/Filter Characteristics

Low energy X-rays in the spectrum of X-rays produced by X-ray tubes contribute little to image characteristics, and are the main source radiation dose to the patient. Hence the need for beam filtration. Recently there has been

growing interest in specialist filter materials using the "K edge" to select those components of the beam allowed to pass. This has particular importance in Mamography where relatively high exposures are used on large number of asymptomatic patients. The X-ray generator waveform is another contributing factor and the trend to HT waveforms that are constant rather than sinusoidal helps to remove low energy, non-image forming radiation.

d) Operator Performance

There are many basic factors determined by the operator which affect the patient dose. Correct beam collimation and the use of minimum field sizes is the most obvious. Appropriate tube-patient distance is another, since patient dose will increase at close distances. Finally repeat films increase patient dose with no diagnostic benefits.

The influence these factors have on patient dose can be summarised as follows:

Equipment	Patient Dose Variability
Rare Earth Screens	3:1
Image Intensifier	5:1
Use of Carbon Fibre	1.7:1
Generator Waveform	2:1
Procedure	
No. of views required	7:1
Film sizes specified	2:1
Screening time	20:1
Field size	2:1
Operator	
Correct collimation	2:1
Optimum KV	1.4:1
No. of repeat films	2:1
Inappropriate use of grid	4:1

RADIATION PROTECTION IN NUCLEAR MEDICINE

Facilities

There is a wide range of unsealed radionuclides used for medical purposes. The hazards associated with them depends upon the procedure being carried out, the toxicity of the compond and the activity involved. IAEA have divided the common rationuclides into various classess of toxicity and laid down limits of activity each class which may be handled in three grades of laboratory.

Grade A laboratories are for handling high toxicity compounds such as alpha emitters and high activities. These are not normally encountered in hospitals.

Grade B laboratories are used for medium toxicity compounds such as Iodine-131, Chromium-51 and activities in the order of GBq.

Grade C laboratories are used for low toxicity compounds such as Tritium, Technetium-99m and lower levels of activity of medium toxicity compounds.

Some hospitals may only require a Grade C laboratory particularly when only invitro tests are being undertaken. However for dispensing of therapy doses the facilities of a Grade B laboratory are required. These include the use of protective clothing, smooth non absorbent surfaces to the benches, floors, walls, direct access to mains drainage etc.

In hospitals when it is likely that materials are to be injected intravenously there is the additional requirement of pharmaceutical safety. Fortunately the facilities required to prepare safe and clean radiopharmaceuticals do not conflict in most cases with those needed to handle radioactive materials. One area in which compromise has to be reached however relates to air flow. Radioactive considerations require that a negative pressure should exist in the laboratory so as to prevent the spread of contamination to the rest of the building in the event of an accident, but for clean or aseptic conditions a positive pressure is recommended in order to exclude dust. The solution chosen depends upon procedures and activies held.

Handling of Radioactive Materials

In most cases the risk associated with the use of radionuclides arises from external radiation from either the bottle or syringe containing the radioactivity or the patient following administration. In order to minimise exposure the main precautions which can be taken are:

a) Minimise the exposure time by carrying out procedures as rapidly as is consistent with the satisfactory and safe performance of the task.

b) Reduce the dose rate by increasing the distance from the source whenever possible e.g. by not standing too close to patients unnecessarily or by using tongs to handle high activities.

c) Use appropriate shielding to reduce dose rates e.g. around syringes when giving injections, or lead pots for bottles.

In addition it is good practice to carry out all procedures involving unsealed sources in shallow plastic dishes preferably lined with absorbent paper. These contain any accidental spillage/contamination. Gloves must always be worn when handling radioactive material and it is important to prohibit eating, drinking or smoking in a radiochemical laboratory to reduce the risk of ingestion of radioactivity.

The disposal of radioactive waste which results from nuclear medicine procedures is also of major importance. In most countries there are regulations which govern the amounts of radioactivity which can be disposed by various means. In general a policy of local disposal by maximum dispersion in non-active material is encouraged. In the case of liquids this means flushing down the drains leading directly to a mains sewer where it is further diluted. Solid waste is disposed ususally by incineration after ensuring good dispersal with non active waste and rapid efficient escape of the gaseouse products. The maximum amounts which can be disposed vary according to the half life of the radionuclide.

Radiation Doses

The use of radiopharmaceuticals necessarily leads to different organs receiving widely different absorbed doses. Using the concept of effective dose equivalent and the weighing factors of organs to take account of the different sensitivities (as well as physical chemical and biological data), Annual Limits of Intake of radiopharmaceuticals have been defined by ICRP to limit the intake of radioactivity into the body to such an amount that the prescribed annual dose equivalent limits are not exceeded.

In the U.K. radiopharmaceuticals can only be administered by medical practitioners who hold an appropriate certificate detailing the description and purpose of the product. The maximum activity to be used in any procedure is specified. This quantity is greatly influenced by the effective dose equivalent. When a procedure results in the effective dose equivalent exceeding 5mSv it is recommended that alternative procedures shold be considered when they are available and practical. It is expected that some of the radioactive products which give rise to radation dose in this category are likely to be replaced by improved products.