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Radiation Safety in Diagnostic Radiology

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RADIATION SAFETY IN DIAGNOSTIC RADIOLOGY

Introduction

There has been a growing awareness in recent years among both the general public and those in medical professions of the possible detrimental effects of ionizing radiation on human beings. This increased awareness can have the desirable effect of inciting efforts to decrease the degree of unnecessary human exposure to radiation. It can also, however, cause irrational fear and misjudgement due to incorrect or misinterpreted information. The result at times is greater harm than the radiation itself could ever cause. A patient refusing needed radiographic examinations solely on the basis of an exaggerated fear of harm from radiation, and the performing of a therapeutic abortion on the basis of a minimal exposure to the fetus are possible examples. The public's increased concern regarding the biological effects of radiation, particularly at low levels, is a healthy phenomenon but it must be nourished with information that is both as correct and understandable as possible. The word understandable is to be emphasized: correct but hard to understand information can cause as serious misconceptions as that which is plainly incorrect.

Radiographers should have a special interest in radiation effects not only for the sake of safety for themselves and patients, but also because of their interaction with the public--they are a prime source of information to the patients. For many people the radiographer is the only person they will encounter who actually works with radiation and who they think might have some knowledge of its properties. A properly informed radiographer is able not only to help reduce the radiation risk to the patient, but also to help soothe any unnecessary fears that might arise.

This paper will try to present the reader with some basic concepts concerning radiation exposure and safety in an easily understandable and useful form. It will try to put radiation risks in perspective with other risks which occur in our daily lives and also give some guidance for reduction of these risks.

The goal of a radiographic examination is to provide a maximum amount of useful diagnostic information at a minimum risk to the patient. To that end, three important concerns should be in the mind of the radiographer:

1. Image Quality
2. Patient Safety
3. Personnel Safety

Satisfactory fulfillment of these concerns is dependent on the performance of both the radiographic equipment and the radiographer. While the appropriateness of the last two items to a discussion of radiation safety is obvious, that of the first item, image quality, may seem less so. In fact, along with the importance of image quality to the obtaining of diagnostic information goes its import to radiation safety: poor quality radiographs that demand retakes require additional radiation exposure to the patient. The last part of this paper will discuss the subjects of image quality, patient and personnel safety. In the first part radiation concepts will be covered, including biological effects and evaluation of risks.

Radiation Units [16, 17, 29]

The amount of radiation received by an individual can be expressed in several ways. One quantity called "Exposure" and given in units of Roentgens, measures the ionizing strength of the radiation: 1 R will cause the production of 2.58×10^{-4} coulombs of ionization per kilogram of air. Another quantity called "Absorbed Dose" is given in units of rads (radiation absorbed dose). 1 rad corresponds to the absorption of 100 ergs of energy per gram of tissue. For water or soft tissues, 1 roentgen is approximately equal to 0.9 rad. A third quantity called "Dose Equivalent" is given in units of rems and is simply the product of "absorbed dose" (rads) times a "Quality Factor" which reflects the relative biological damage caused by different forms of ionizing radiation (x-rays, beta particles, alpha particles, neutrons). Since the quality factor for x-rays is 1.0, the expression of radiation quantity in either rads or rems will be numerically equal in

diagnostic radiology. The small difference numerically for expression in Roentgens is often ignored so that Roentgen, rad and rem are commonly used interchangeably.

In diagnostic radiology, use this approximation:

$$1\ R \doteq 1\ rad = 1\ rem$$

For the rest of this discussion I will use these units and the terms "exposure" and "dose" interchangeably.

For discussions involving low levels of radiation, the prefix "milli" $= \frac{1}{1000}$ is often used (and abbreviated "m"), so that:

1000 mR = 1 R	1 mR = $\frac{1}{1000}$ R
1000 mrad = 1 rad	1 mrad = $\frac{1}{1000}$ rad
1000 mrem = 1 rem	1 mrem = $\frac{1}{1000}$ rem

Biological damage from radiation depends not only on the dose to the tissues but also on the size of the area irradiated. This effect, however, has not specifically been included in the previously discussed units.* If the area of a patient that is irradiated is reduced by proper collimation to the area of interest, the radiation risk to the patient would be reduced even though an expression of his radiation dose in roentgen, rad, or rem would remain the same.

In order to explicitly incorporate the effect of irradiation-area on biological risk, a quantity called "exposure area product" has been proposed and its unit is the rap. To obtain the exposure area product (E.A.P.) produced by an x-ray exposure, multiply the exposure in roentgens by the area irradiated expressed in square centimeters and divide by 100. As an example, if a patient is exposed to 0.5 R with a radiation field size of 15 cm x 20 cm the E.A.P. is $\frac{0.5 \times 15 \times 20}{100} = 1.5$ rap.

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*Note: If a patient is irradiated twice in the same place of the body with a dose of 100 mrem, the total dose is 200 mrem. If the second irradiation occurs to a separate, non-overlapping part of the body from the first, the total dose is only 100 mrem in this case, but the area receiving this dose is larger.

Sources of Radiation

Radiation of various forms is a normal part of man's natural environment [8,19,20,25,30]. This natural background radiation is made up of cosmic rays from outer space and terrestrial radiation from radioactive materials in the earth in about equal proportions. A third source is from small amounts of naturally occuring radioactive materials that reside in our bodies. The actual background radiation levels vary significantly from place to place; following are approximate average values to give some starting point for an understanding of relative radiation doses:

Natural background radiation:

100 mrem/year - total from cosmic rays and terrestrial radiation
25 mrem/year - from internally deposited radionuclides

These doses are referred to as being "whole body" since the irradiation is to the entire body.

By far the main source of man-made exposure to radiation is diagnostic x-rays:

From medical procedures:

Roughly 75 mrem/year - average per person in the U.S.

Note that this additional exposure is less than the amount from natural background. Also it is not "whole body" irradiation.

Compare this average total radiation exposure of about 0.2 rem/year with the median lethal "whole body" dose for an acute exposure and also with the minimum dose required to produce symptoms of radiation sickness: [16, 17, 24, 29]

Lethal whole body dose $\doteq$ 450 rem
Minimum symptomatic dose (vomiting) $\doteq$ 100 rem

There is a wide separation between 0.2 rem and 100 rem. Since radiation from both natural and diagnostic x-ray sources is definetly in the sub-symptomatic range, one would expect that any biological effects that would result from such irradiation would be subtle and difficult to determine.

It should now be instructive to see how specific radiological examinations compare to each other and to the natural radiation background in the amount of radiation exposure they produce. The following table includes several common examinations [14]. The figures given are typical radiation exposures for single films not total exposures for multi-film examination. Note also that there exists a great variation in actual individual exposures from these figures due to differences in patient size; equipment: x-ray generation type and calibration, beam filtration, screens, and grids; technique setting; etc. This variation can be greater than a factor of ten.

Typical radiation exposure to adults from diagnostic x-rays:

	Exposure (mR)	Exposure Area Product (rap)
Natural background (total for one year)	125	6.0
Chest (P/A)	23	0.5
Skull (Lat)	270	1.3
Abdomen, KUB (A/P)	560	4.7
Retrograde pyelogram (A/P)	590	5.5
Thoracic spine (A/P)	690	4.9
Lumbar-sacral spine (A/P)	790	6.6
Computed tomography (single scan)	2500	6.0

Estimating Patient Exposure

There are several different methods, of varying accuracy, for estimating patient exposure for a single film. First I will discuss a simple method that can be used without reference to tables, graphs, or measuring instruments by simply remembering a very few small numbers. By this method you can usually estimate exposure to about a factor of two, which is much better than having no idea at all of what the exposure is.*

What numbers do you have to remember? Just three of them: 5, 10, and 25! It goes like this: Assume a technique setting of 80 kVp and a focal spot to film distance (F.F.D.) of 40 in. (100 cm.)--this would mean a focal spot to skin surface distance of about 30 in. (75 cm.). The radiation

*A poorly calibrated x-ray unit can add another factor of two error to the exposure estimation. This method is solely designed to give you a chance to obtain a very approximate dose figure with a few seconds of mental figuring. It is not intended to replace more sophisticated methods when accurate dosimetry results are required.

exposure to the patient, in this case, is about /10 mR/mAs/. For a technique of 60 kVp, the exposure would be /5 mR/mAs/, while at 120 kVp it would be /25 mR/mAs/. To estimate actual exposure for a particular mAs setting exposure, simply multiply the appropriate number (5, 10, or 25) by the mAs setting. If the focal spot to film distance were 72 in. rather than 40 in., simply divide the exposure you get by four.

As an example suppose you use the following technique: 80 kVp, 400 mA, 0.1 sec. Then the calculation goes like this:

10 mR/mAs x 40 mAs = 400 mR

For a F.F.D. of 40 in., the exposure would be approximately 400 mR. For a F.F.D. of 72 in. (focal spot to skin distance of about 60 in.), it would be one-fourth that or 100 mR.

Exposure estimate for 40 in. F.F.D.

60 kVp: 5 mR/mAs
80 kVp: 10 mR/mAs
120 kVp: 25 mR/mAs

The obvious advantage of this method is that you can come up with rough estimates for any exposure after a few seconds of mental figuring.

What are the major sources of inaccuracy for the previous method? Differences in generator type (3ϕ generators give out 25-50% more radiation than a 1ϕ generator at the same technique setting), beam filtration, and differences between indicated and actual kVp, mA, and time settings all contribute to exposure variations. The next method takes into account the first two factors and also gives you values for arbitrary kVp's.

The following table provides numbers to replace the 5, 10, and 25 of the previous method. These exposure numbers are given for 80 kVp, 30 in. (75 cm) focal spot to skin distance using either 1ϕ or 3ϕ machines, and for various values of half value layer measured at 80 kVp. The half value layer (HVL) of an x-ray unit (measured at some fixed kVp, here 80 kVp) is an indication of the amount of filtration between the tube and patient, and this of course affects the radiation output. (More will be said later about HVL). HVL is given in units of mm of aluminum, but do not confuse this number with total filtration amounts given in the same units. The two numbers are related but they are not the same number.

Radiation exposure at 30 in. (75 cm) from the tube focal spot for single phase (1ϕ) and three phase (3ϕ) machines:

HVL (measured at 80 kVp):	2.3 mm Al	2.5 mm Al	3.0 mm Al	3.5 mm Al	4.0 mm Al
1ϕ:	12.4 mR/mAs	11.0 mR/mAs	8.7 mR/mAs	7.0 mR/mAs	
3ϕ:	18.0 mR/mAs	16.0 mR/mAs	11.8 mR/mAs	8.7 mR/mAs	6.7 mR/mAs

To use this table, find out the HVL of the x-ray unit at 80 kVp and determine if it is a 1ϕ or 3ϕ unit. Then read out the exposure number from the table. If an exposure was made at 80 kVp and the focal spot to skin distance was about 30 in., then simply multiply the number by the mAs to get the patient exposure. If the kVp or focal spot skin distance are different than the above value, use the following equation:

$$\left[\begin{array}{l}\text{Exposure}\\ \text{Number}\\ \text{From}\\ \text{Table}\end{array}\right] \times \left[\frac{\text{kVp}}{80}\right]^2 \times \left[\frac{30 \text{ in.}}{\text{Focal spot to skin distance}}\right]^2 \times \text{mAs}$$

= Patient Exposure

As an example, suppose an exposure was made at 90 kVp, 200 mA, 0.5 sec, and the focal spot to skin distance was about 60 in. The machine used was 3ϕ with a HVL of 3.0 mm Al. First look at the exposure table and obtain the number 11.8 mR/mAs; then use the above equation:

$$(11.8 \text{ mR/mAs}) \times \left[\frac{90}{80}\right]^2 \times \left[\frac{30 \text{ in.}}{60 \text{ in.}}\right]^2 \times 10 \text{ mAs}$$

= 11.8 mR/mA x 1.27 x 0.25 x 10 mAs

= 37 mR

Notice that the exposure number obtained from the table is a fixed number for a particular machine as long as its filtration is not changed. Each x-ray unit could simply have the appropriate number written by it and then the table would not have to be referred to. An even better idea is not to use the table at all, but to make an actual measurement with a radiation detection device of the exposure per mAs at 80 kVp and 30 in. from the focal spot. This third method is, of course, the most

accurate. (The exposure values from the table can be off by as much as a factor of two for a poorly calibrated x-ray unit). It is implemented in the same way as the second method except the value from the table is replaced by a more accurate measured value.

What about fluoroscopic exposure? You can use exactly the same table and formula as before simply remembering that for "under the table" tubes, the distance from the focal spot to the table top (and, therefore, to the skin surface) is about 18 inches and the mAs is simply the mA reading multiplied by the fluoro time in seconds (not minutes). Here's another example:

> Suppose the tube has a HVL of 2.5 mm Al and is running at 70 kVp and 3 mA with a 3ϕ generator, the total fluoro time is one minute, and the tube to table top distance is 18 in. The exposure number from the table is 16.0 mR/mAs:
>
> $$\text{Patient exposure} = (16.0\ \text{mR/mAs}) \times \left(\frac{70}{80}\right)^2 \times \left(\frac{30}{18}\right)^2 \times 3\text{mA} \times 60\ \text{sec}$$
>
> $$= 6125\ \text{mR} = 6.1\ \text{R}$$

One minute of fluoro has exposed this patient to 6.1 R of radiation. The maximum <u>legal</u> limit for patient exposure in fluoroscopy is 10 R/min.

In this case, as with film exposures, the most accurate method of estimating exposures is to measure the actual exposure rate (in mR/mAs) at the table top at 80 kVp and substitute the measured number for the value from the table. However, if you would like a very quick and simple way of estimating fluoro exposure with reasonable accuracy use the following approximation:

> <u>For every mA of fluoroscopic technique, one can assume a patient exposure of 2.0 R/min</u>.

You can then see that a 1 min. exposure at 3 mA would cause a patient exposure of 6.0 R from this rule which happens to agree closely with the previous typical calculation.

<u>Instruments for Radiation Measurement</u>*

The instruments useful for radiation detection or measurement in diagnostic radiology are of four main types: (1) ionization chambers, (2) Geiger counters, (3) TLD's (thermoluminescent dosimeters), and (4) film. The following page shows some pictures of examples of the first two types. (The general term for an instrument that registers the total dose received by it is a "dosimeter").

The most accurate of these instruments are the ionization chambers. They measure the amount of ionization produced by radiation in a sensitive volume (chamber) filled with air. An electronic exposure meter utilizing ionization chambers can be purchased for $2,000 to $3,000. (Though one, compact, simple version is available for $625). An example is shown in Fig. A. This kind of instrument is very accurate and sensitive, usually capable of measuring fractions of an mR. Another instrument which employs an ion chamber is a portable survey meter, sometimes referred to as a "cutie-pie" (its code name at Los Alamos where it was developed). It is shown in Fig. B. Its cost is from $600 to $1,000. Units utilizing either mechanical movements (like the one shown) or the newer electronic readout displays are available. A third type of ionization chamber is the pocket dosimeter--essentially an air filled capacitor (the ionization chamber) which is charged up and then discharged by the ionization produced by radiation. It consists of two parts: (1) the ionization chamber itself shown on the right which also contains an optical scale indicating the amount of charge left in the unit and reading directly in <u>mR</u> or <u>R</u>; (2) the charging unit which will adjust the optical scale to zero by recharging the chamber for each use. Pocket dosimeters are relatively inexpensive (about $100 for a dosimeter and about $100 for the charging unit), and are small enough to be worn for personnel dosimetry.

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*The tasks of radiation dosimetry and quality control properly belong to the hospital's radiation physicist. However, I think it is useful for radiographers to have some idea of the instruments and types of measurements involved in this work. The radiographer could very realistically become involved in the implementation of a program of quality control by performing measurements under the supervision or instruction of the physicist. This paper is not intended to give that instruction but only a brief overview of the subject.

The most common type of Geiger counter used in diagnostic radiology is the audible exposure monitor or "chirper" (Fig. D). This unit responds to a radiation field by "chirping" at a rate proportional to the radiation intensity. It is portable so that it can be worn as a personnel monitor, and is sometimes used to demonstrate ways of reducing radiation exposure during fluoroscopy. It is different from the previously discussed instruments in that it does not usually give numerical readings.* However, it can be very roughly calibrated by comparison with ion chamber to determine what fraction of an mR is represented by each chirp. For diagnostic radiology only those units, like the one shown, which have a high sensitivity, and whose energy response is significant in the diagnostic x-ray region are suitable (some units are only sensitive to the higher energy x-rays and γ-rays found in nuclear medicine or radiotherapy). Suitable units are usually advertised for use in fluoroscopy (or diagnostic radiology) and cost around $150.

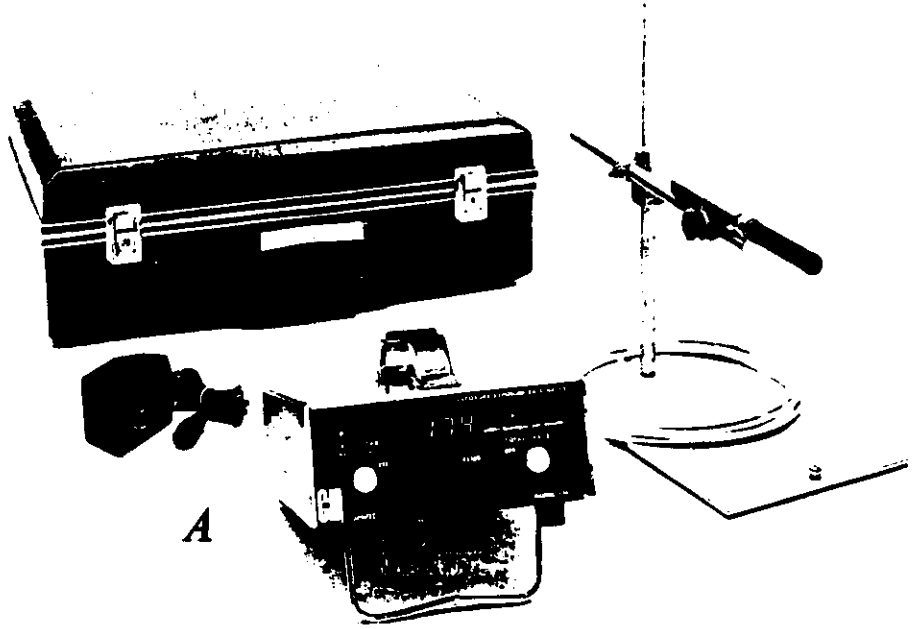
Film and TLD's are employed in the personnel badges used for radiation monitoring. In addition TLD's can be used for monitoring the radiation exposure in various locations in the x-ray department and also to determine patient exposure to high accuracy. TLD's are very small wafers of a material with a special property: if irradiated, they will glow with light if later heated; the amount of light given off is proportional to the radiation exposure.

Uses and Advantages of the Various Radiation Detection and Measurement Instruments:

1. Equipment quality control (also to determine patient exposure from quality control measurements).
   A. Electronic exposure meter--greater accuracy, sensitivity, and dynamic range than pocket dosimeter; easier and quicker to use.
   B. Pocket dosimeter--adequate accuracy for most uses, inexpensive, can double as a personnel monitor. Note: pocket dosimeters come in various sensitivities: 0-200 mR, 0-500 mR, 0-1 R, 0-5 R. For maximum accuracy, you should use the one

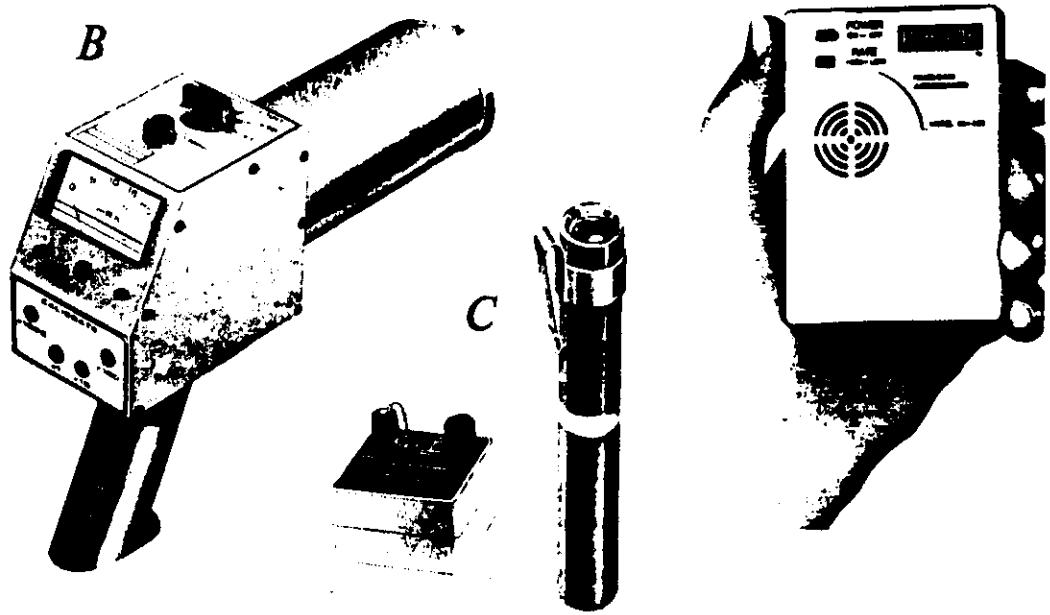
*Those that do give numerical readings cannot be relyed upon to give even approximate information on the doses received for x-rays of energies typical in diagnostic radiology--Geiger counters are simply not suitable for making accurate dosimetry measurements.

DIARAD III DOSIMETRY SYSTEM



A

CUTIE PIE SURVEY METER



B

C

D

with the smallest mR rating that will cover the expected range of possible exposure. (The accuracy is about 10% of the full scale reading.)

Note: While the pocket dosimeter is often chosen because of the great price difference between it and the electronic exposure meter, the introduction of a relatively inexpensive electronic meter ($625) should cause it serious competition.

2. Checks of shielding adequacy; area radiation monitoring.

   Radiation from single x-ray exposures:

   A. Portable survey meter--accurate numerical output, sensitive.

   B. Audible radiation monitor--very sensitive, but does not give any numerical reading. Thus only good for qualitative checks.

Note: Both of these instruments respond only to the rate of radiation during the exposure--they do not make a reading of the total exposure that can be inspected after the exposure is over. For this reason they are only useful if the exposure time is long, of the order of a few seconds.

   Radiation from multiple x-ray exposures over a period of time:

   A. TLD--accurate; can be used for a long monitoring period--for example, one month--so that equipment workload is directly taken into account.

3. Patient radiation monitoring

   A. TLD--accurate, small size: can be placed on patient without interfering with the image. A unique service is provided by Radiation Monitoring by Mail (RM^2) in Madison, Wisconsin. This service costs about $40 and provides TLD's which, after exposure, are returned to RM^2 for reading. A report is then mailed to the purchaser of this service detailing the doses measured by the TLD's. This is a very accurate and inexpensive way of determining typical patient exposures and discovering if the exposure levels are acceptable. (This service can also be used for area radiation monitoring.)

4. Personnel radiation monitoring

   A. TLD Badges--advantage over film: more accurate and sensitive, can detect a large range of exposures, less sensitive to heat and humidity, more stable over time, insensitive to exposure from light.

   B. Film Badges--can possibly discriminate between a single or multiple exposure.

   C. Pocket dosimeter--disadvantages: larger, less convenient to wear than a badge; can lose its reading if dropped; less accurate for monitoring over long times; advantage: any exposure can be immediately read on the dosimeter.

   D. Audible exposure monitor--advantages: any exposure is immediately indicated by warning "chirps"; the frequency of the chirping gives an indication of the relative intensity of the radiation field; very sensitive. Disadvantages: useful only in continuous radiation fields (fluoroscopy); will give no indication of the severity of an instantaneous exposure; does not give a numerical figure for total radiation exposure.

Maximum Permissible Dose

Perhaps this should be better called the recommended maximum permissible dose: there is no actual federal regulation for diagnostic radiology, though some states have enacted statutes concerning dose limits. The national body involved in making limit recommendations is the NCRP, National Council on Radiation Protection and Measurements. Quoting from this organization's publications:

> For radiation protection purposes, people are divided into two classes. First are those classified as radiation workers who incur a certain likelihood of exposure to ionizing radiation in the course of their normal duties as an occupational risk. The risk incurred is slight and is to be accepted in the same way as risks by workers in other fields such as electricians, chemists, biologists, and sanitary engineers. These workers should receive instruction or training regarding radiation procedures. The radiation limits pertinent to the protection of such individuals are called maximum permissible doses. The maximum permissible dose for a radiation worker is 5 rem in any one year. Irradiation at the level of the maximum permissible doses is not to be considered as desirable. In every case, the dose should be kept as low as practical.
>
> The limit for members of the general public is one-tenth of the total body limit for radiation workers, that is, 0.5 rem per year. Those not specifically classified as radiation workers are considered members of the general public. [26]

The ICRP (the international counterpart of the NCRP) has the following to say about maximum permissible doses:

> The permissible dose for an individual is that dose, accumulated over a long period of time or resulting from a single exposure, which, in the light of present knowledge, carries a negligible probability of severe somatic or genetic injuries; furthermore, it is such a dose that any effects that ensue more frequently are limited to those of a minor nature that would not be considered unacceptable by the exposed individual and by competent medical authorities.
>
> Any severe somatic injuries (e.g. leukemia) that might result from exposure of individuals to the permissible dose would be limited to an exceedingly small fraction of the exposed group; effects such as shortening of life span, which might be expected to occur more frequently, would be very slight and would likely be hidden by normal biological variations. The permissible doses can therefore by expected to produce effects that could be detectable only by statistical methods applied to large groups. [20]

In general, maximum permissible doses are given not only for whole body exposures but also for exposures to selected organs or parts of the body which may be allowed higher levels. The currently accepted guidelines for both radiation workers and the general public are given in the following table:

Maximum permissible dose (rem) for one year [24, 26]

Occupationally exposed:	
Whole body	5 rem
Gonad, lens, bone marrow	5 rem
Hands	75 rem
Forearms	30 rem
Other organs	15 rem
Fetus (entire gestation period)	0.5 rem
Not occupationally exposed:	0.5 rem

It should be a relatively uncommon instance that anyone in a diagnostic radiology department would reach the limit of 5 rem/year. Usually only a small fraction of the workers would receive a whole body exposure greater than 0.5 rem/year, and so it is usually reasonable to set a 0.5 rem/year limit as a desirable goal.

Biological Effects of Radiation [8,13,16,17,20,21,22,23,24,26,27,28,29,301,31,34]

The biological effects of radiation can be divided into two classes: somatic and genetic. Somatic effects manifest themselves in the individual irradiated while genetic effects are manifested in the offspring and future generations.

Because of the very common natural occurence of cancer or genetic defects, it is very difficult to detect a small relative increase in their occurrence due to low levels of radiation, even though the absolute numbers of people affected may not be small. In addition, many other environmental factors (natural and man-made) can have significant carcinogenic and mutagenic effects which cannot be ignored in studies of the effects of radiation on human populations and which make evaluation of the radiation risk difficult. I will try to present some figures of risk for the biological effects of radiation, but remember that these figures are only approximate: the estimates of risk by the experts typically vary by a factor of ten. Also keep in mind that the damage caused by radiation is dependent not only on the total dose delivered but also on the dose rate: an amount of radiation delivered in a short time is more damaging than the same amount delivered over a longer time. Of course, it is also dependent on the size and location of the area irradiated.

Genetic Effects. The genetic effects of radiation have been extensively investigated in animal studies, most noteably involving the fruit fly and mice, and its deleterious action is well documented. Irradiation of the reproductive organs can produce both gene mutations and chromosome damage that can manifest itself in future generations. Available human data is very spare in comparison; studies from Nagasaki and Hiroshima following the atomic blasts have thus far been inconclusive with respect to mutagenesis. The genetic risk to humans must presently be extrapolated from the animal studies.

The dose required to double the mutation rate in man is currently estimated to be 50-200 rem.[23,30] It is also estimated that parental exposure of 1 REM will produce 60-1,100 additional genetic disorders per million live offspring.[23,30] This estimate should be compared to the natural incidence of genetic deffects in the general population. That incidence is about one serious genetic disorder that will manifest itself sometime during the life of the individual for every ten live births.[23]

In general, the testes appear to be more sensitive to irradiation than do the ovaries.[34] A single acute exposure is more damaging than the same total dose spread over a period of time. Further, the genetic consequences

can be reduced if adequate time is allowed to elapse between radiation exposure and conception. This period is about two to six months for men and probably somewhat longer for women.[34]

Somatic Effects. It has already been mentioned that 450 rem is the approximate whole body lethal acute dose, while 100 rem is the minimum acute dose that can cause physical symptoms. The effects of radiation in these high dose ranges are due directly to cell sterilization and death. Other somatic effects include induction of cataracts which usually appear only after the accumulated dose to the lens of the eye has passed a threshold of about 400-500 rem [16,17,23,29]

In diagnostic radiology we are usually concerned with much smaller doses for which there is little reliable data on biological effects: our estimates of effect must somehow be extrapolated from information on high dose effects. When this is done the principal concern seems to be carcinogenesis. Acceleration of the aging process and, therefore, life-shortening is also a possibility but this has not yet been reliably demonstrated to be an effect in man.

Human data concerning carcinogenesis is much more substantial than is the case with genetic effects, and includes information involving cancer induction in early radiation researchers, uranium miners, radium dial painters, and patients receiving therapeutic radiation for various ailments including treatment of ankylosing spondylitis, metropathia hemorrhagia, and thymus enlargement.[34] Some of the best human data, however, has been derived from Hiroshima and Nagasaki where the incidence of leukemia rose during the first decade after the blasts. The incidence varied with the proximity of the subject to the explosion and was therefore dose dependent. After twenty years, additional excess cases of leukemia were markedly reduced from the peak incidence (at 10-15 years post-irradiation). However, as the bomb survivors were studied for longer periods, there also appeared a significantly higher incidence of lung, breast, and thyroid cancer reflecting the longer latency period of these cancers.[23,30,34]

A rough estimate of the risk of cancer mortality from low level radiation is one extra cancer death for every 10,000 man-rems of whole-body radiation. Another way of putting it is that being exposed to 1 rem of radiation gives you a 1 in 10,000 extra chance of developing a fatal cancer sometime later in life, over and above your normal cancer risk.[23,30]

The tissues most vulnerable to radiation appear to be the marrow, female breast, and thyroid.[23] The figure of risk quoted above is an average over age and sex. The risk generally increases at younger ages; the risk of cancer for females is greater than that for males because of an increased susceptibility to thyroid cancer and, of course, breast cancer.[23,30,34]

Suppose you were a radiation worker who was exposed to 5 rem of radiation per year (the maximum allowable dose) for 20 years. The total dose over that period would be 100 rem. Induction of cataract would not seem very unlikely since the exposure is well below estimated threshold. Chances of a radiation induced cancer would be about 1 in 100 as a conservative estimate, these are not very severe risks as they stand, but I think you can see why the allowable dose is not set much higher.

Concerning risk to the patient in a radiographic examination, it is obvious that a chest x-ray at 1/40 rem is a really negligible risk. Even if the patient went through an examination involving a 10 rem exposure, the chance of that radiation producing cancer comes out as 1 in 1,000 (actually somewhat less, since only part of the body is irradiated) so that this should not cause the patient any great concern. It should be of some concern to the radiographer. Though the risk to any one patient is very small, the total risk that some one of the many individuals examined in a radiology department may develop cancer as a result of radiation, could be substantial. It is here that good radiological practices by the radiographer could save lives by reducing radiation exposure.

Probably the most serious risk from diagnostic x-rays involves developmental effects on the new-born child from irradiation in the uterus. It is here that relatively low doses of radiation can have the most damaging effects. Evidence exists in animal data of damage caused by doses as low as 5-10 rem (at the fetus). Animal studies indicate the frequency of occurence of a particular defect caused by irradiation in utero is both dose dependent and crucially dependent on the day of gestation on which the exposure occured.[34] Available human studies involving therapeutic irradiation and exposure to the A-bomb at Hiroshima confirm the deleterious effects of in utero exposure for relatively large doses. Because of difficulties in analysis of the human data for low doses, reports on the consequences of exposures at the diagnostic level give conflicting conclusions.

The greatest sensitivity to radiation for the embryo-fetus is from the second to ninth week after conception--the period of major organogenesis. Previous to this time, in the pre-implantation period, radiation will generally either kill the embryo or not harm it. Central nervous system development occurs over a considerably longer period than does major organogenesis and so the C.N.S. endures an extended period of sensitivity to radiation. Human abnormalities caused by in utero irradiation include growth retardation, central nervous system defects (microcephaly, mental retardation), and other gross congenital malformations, in addition to subtle functional disabilities and increased post-natal risk of developing leukemia and other cancers. [8,17,23,27,29,30,31]

Here, there also appears to be a dependence of effect on dose rate: Spreading the dose over a longer period (while keeping the total dose the same) usually reduces the chance of abnormalities. In any case, the sensitivity of the developing fetus to radiation demands that great care be taken to avoid any unnecessary exposures even to relatively low radiation levels. Shielding of the fetus while other areas of the mother are irradiated will essentially prevent any harmful effects to the fetus. If an exposure does unknowingly occur, however, the risk to the fetus due to the radiation must be compared to the normally significant risk associated with any pregnancy. This relative risk is currently believed to be small at fetal doses of 10 rem or less.

Comparison of Risks

A comparison of the risks of radiation to other more familiar risks can be very enlightening. It can be useful in conveying a proper perspective on radiation risk to the patient--helping to give reassurance to someone who is fearful of radiation due to an overblown concept of the risk involved. Some comparisons can be made even without direct reference to "risk" in explanations to the patient: The typical variation in the yearly dose delivered by natural background radiation in American cities is 60 mrem at different locations within the same city. [25] This is worth about two to three chest x-rays. You surely do not worry about background radiation level in deciding where to live or work in a city, why should you worry about a chest x-ray?

The comparison of risks is presented here in three different forms: [1,2,3,4]

Chance of Serious Injury or Death

Auto accident (serious injury)	1 chance in 100 per year
Cancer, all types and causes	1 chance in 700 per year
Auto death	1 chance in 4,000 per year
Fire death	1 chance in 25,000 per year
Death from the "pill"	1 chance in 25,000 per year
Drowning	1 chance in 30,000 per year
Risk of cancer from 1 rem of radiation	1 chance in 10,000 per exposure
Risk of cancer from 1 chest x-ray	1 chance in 500,000 per exposure

Equivalent Risks

1 chest x-ray (25 mrem)	crossing street 100 times driving 100 miles additional risk from driving 400 miles without a seat belt smoking four cigarettes

Loss of Life Expectancy

1 chest x-ray	35 minutes
coast to coast flight	100 minutes
1 rem of radiation	1 day
Driving a car 10,000 miles	3 days
Average male smoker	6.2 years
Average female smoker	2.2 years

The risk to individuals receiving diagnostic x-rays is generally very small (except perhaps for some cases of fetal irradiation). Nevertheless, since large numbers of people are exposed to diagnostic x-rays and the small individual risks add up, it makes sense to reduce radiation exposure as much as possible (consistent with maintaining necessary diagnostic information).

Patient Safety

Several steps can be taken to reduce patient exposures, as outlined below: [8, 19, 29]

1. Reduce the number of repeat examinations

   Obtaining a good quality radiograph on the first try is dependent on the performance of both the x-ray equipment and the radiographer. The first can be improved by the implementation of a program of equipment quality control. The second by the proper use of technique charts along with a familiarization of the ways in which kVp, mAs, and patient thickness affect film density. (Example: An increase in patient thickness of 3 cm generally demands a doubling of mAs or a raising of kVp by 15%--is a rule that works in many cases.) Sometimes, a simple change in technique can help improve chances for a good image: use the highest mA allowed for the focal spot and kVp employed, so that the exposure time can be shortened and motion blur reduced.

2. Use the highest kVp that permits a good diagnostic image

   Raising the kVp will reduce image contrast; it is this effect that determines the highest kVp at which an image with an acceptable level of contrast can be obtained. Suppose a study which had been done at 70 kVp is found to still give good quality images at 80 kVp. By raising the kVp by 10 kVp (15%) you can cut the mA in half. The study at 80 kVp will then give only 65% of the patient dose of the one done at 70 kVp.

3. Use faster intensifying screens

   The recently introduced rare earth screens have twice the sensitivity of calcium tungstate screens of comparable sharpness. This means you can cut patient dose in half without sacrificing image quality, for example, by changing from Hi-plus to Lanex or Quanta III rare earth screens. This change has the additional benefits that the tube loading is cut in half, shorter exposure times or a smaller focal spot can be used, and very large patients are easier to radiograph. What must be kept in mind when considering the use of rare earth screens is their high cost compared

to conventional screens, and their use of green sensitive film instead of the regular blue sensitive kind. Great care would have to be exercised in a department that used both rare earth and conventional screens to avoid any mixup of film types.

A further consideration in screen choice is which model of a particular screen type is to be used for various procedures. Even using Hi-plus is an improvement over using par speed screens if the extra detail provided by the par screens is not needed for accurate diagnosis.

4. Carbon fiber cassette fronts and table tops

   By the use of low attenuation carbon materials in both cassette fronts and table tops, manufacturers claim that patient dose can be reduced as much as 30% to 50%. The disadvantage of these materials again is their current high cost.

5. Use tight collimation

   A properly collimated x-ray field means a smaller irradiated area—less radiation risk to the patient. Good collimation has the added bonus of improved image quality: The smaller the area irradiated, the less scatter produced and the higher the image contrast.

6. Patient area shielding [15]

   Shielding which attenuates the x-ray beam to about 5% or less of its incident intensity is often used to protect especially sensitive tissues such as the lens of the eye and the gonads. This shielding can be, for example, in the form of small goggles, gonadal cups, or rubberized lead sheets that can be cut to size. Some guidelines concerning area shielding:

   a) Gonad shielding should be considered for all patients with reproductive potential.
   b) Gonad shielding should be used when the gonads lie in or near the primary beam.
   c) Proper patient positioning and beam collimation should not be relaxed when shields are in use.
   d) Shielding should only be used when it does not interfere with obtaining the required diagnostic information. Thus for male

patients, gonad shielding can be used in the majority of x-ray examinations, whereas shielding the ovaries of female patients may frequently obscure visualization of adjacent structures. Eye shields must be used with special care to avoid interfering with the image. They cannot be used in computed tomography because of the severe artifacts produced if they interfere with the primary beam.

7. Proper beam filtration

Patient exposure can be significantly reduced by the addition of a proper amount of filtration to the x-ray tube: This preferentially filters out low energy x-rays that contribute significantly to the patient's radiation dose, but very little to the final image. For this reason all x-ray tubes must have a minimum amount of added filtration to be operated legally. A half-value layer test can be performed on an x-ray unit to see if it satisfies this required minimum filtration regulation.

8. Ask if there is ANY possibility of pregnancy (being mindful that contraceptives can fail)

This will probably be your most important concern regarding radiation safety because of the real possibility of danger to the embryo-fetus at exposure levels that are sometimes found in diagnostic radiology. If pregnancy is a possibility, radiographic examination of the pelvis or abdomen should be delayed to the first ten days after the onset of menstruation, if possible. [8, 28] The x-ray procedures which fall under this "10-day rule" include lumbar spine, hip, urography, pyelography, urethrocystography, pelvimetry, and barium enema.

In the pregnant patient the fetus should be shielded as much as possibly in any x-ray procedure. Any procedure which exposes the fetus to the direct beam should be delayed, if possible, to the third trimester or, even better, after completion of the pregnancy. These delays should be applied in situations where the diagnostic procedure is considered as elective or not of significant immediate necessity to the patient. If there is significant medical need for an immediate radiological

examination it must not be denied to the patient. This is obvious even in a consideration of risk solely to the fetus: The risk to the patient of not having the examination is also an indirect health risk to the fetus. It may help in the judgement of individual cases to point out that the risks to the fetus are believed to be minimal at a fetal dose of 5 rem or less. The actual dose to the fetus will be less than the mother's skin dose and in practically all cases will be less than one-half of the skin dose. Usually only fluoroscopy or a series of several abdominal radiographs will then have a chance of giving a fetal dose above 5 rem.

Personnel Safety [8, 26, 27, 29]

Again, I will outline some important points for radiation safety:

1. Wear lead aprons during fluoroscopy, when operating portable x-ray units, or any time you might be receiving scattered radiation from the patient. It is important to take proper care of aprons. They should be hung by the shoulder straps when not in use. Repeatedly folding them or throwing them in piles will weaken the interior lead shields and eventually cause cracks to appear in them.
2. Patient holding should be done by friends or relatives wearing aprons when feasible, rather than by radiology personnel.
3. Make use of permanent and portable shielding. You should be able to observe the patient behind a barrier of leaded glass, when making an exposure at a fixed radiographic unit.
4. Wear your film or TLD badge and hand it in on time (don't wash or dry it).
5. The badge should be worn on the collar (or the sleeve) outside the apron when a lead apron is used. It must be worn outside the apron in order to monitor possible radiation to the lens of the eye which is not shielded, and whose maximum permissible dose is 5 rem/year, the same as the "whole body" limit.
6. Keep a maximum distance between yourself and the patient whenever possible in fluoroscopy and portable radiography. During spot filming you can step back away from the table after initiating an exposure.

7. Personnel involved in special procedures whose hands are in close proximity to the direct beam should wear ring dosimeters.
8. Quickly notify your supervisor if you suspect you are pregnant.

If you have a high sensitivity audible exposure monitor (chirper), there is a quick and easy way to check for the presence of lead shielding in the walls or windows of an x-ray room. Fully open the tube collimators so that x-rays can scatter off of a large area of the patient table. Set the chirper on high sensitivity and position it on the inside of the room next to the shielding you wish to test. Set the exposure timer to 2 sec. or longer and make an exposure at about 100 mA. You should hear a rapid series of individual chirps. If it is not rapid, take another exposure at a higher mA and/or kVp being careful not to overload the tube. Now take the chirper and place it on the other side of the shielding and expose again. The chirper should be much quieter, perhaps giving out at most one chirp. This difference in the activity of the chirper indicates the effectiveness of the shielding. This simple procedure is not intended to be a full test of shielding adequacy--that would be more involved--but it may satisfy your curiosity as to whether, for example, the viewing port is actually leaded glass or regular glass.

Quality Control* [8, 9, 10, 11, 12, 17, 18, 29, 32, 33]

Proper maintenance of radiographic equipment is essential to insure good image quality, patient, and personnel safety. To this end, a program of quality control should be instituted involving regularly scheduled equipment surveys to determine when maintenance or repairs are required. Following is a list of some of the tests which should be included in any quality control program along with some hints for record keeping.

1. Check lead gloves, aprons, and patient shields, under fluoroscopy if possible, to detect any radiation leaks.
2. Verify the adequacy of any new or unknown room shielding.
3. Check all cassettes for proper film-screen contact (preferred tool: perforated metal test tool).

*See note at bottom of page 9.

4. Processor quality control: Perform daily sensitometry check on base fog, speed index, and contrast (tools: sensitometer and densitometer).
5. Record keeping for x-ray units: At the University of Wisconsin we have instituted a dual system of record keeping. The first part involves attaching a book to every x-ray generator which contains a complete history of malfunctions, repair, and any of out-of-tolerance findings of quality control surveys. This makes it easy for the radiographer to record any malfunctions for future reference and also allows him to check on the condition of the unit from other's comments in the book. The repairman also finds the records of malfunctions very helpful. The second part of this system involves maintaining a quality control notebook for every x-ray tube, in which are kept the filled out quality control forms and test films for that tube.
6. The adequacy of the filtration in the x-ray beam is determined by a measurement of beam quality (also known as a half-value layer measurement). The half-value layer of an x-ray beam is given in units of millimeters of aluminum. It is defined as the thickness of aluminum that if placed in the x-ray beam as extra filtration (over and above that normally present) would reduce the measured x-ray intensity by one-half. The higher the HVL measurement, the more penetrating the radiation, and the less surface dose needed to get a good film. In order to protect the patient from the unnecessarily high doses that would result from machines with low values of HVL, the federal government has set minimum legal levels for this measurement. Since the HVL depends not only on the amount of tube filtration but also on the kVp (it goes up with kVp), the regulations give different minimum values for the HVL, depending at what kVp the measurement is made. As examples: at 80 kVp the minimum legal HVL is 2.3 mm Al, while at 90 kVp it is 2.5 mm Al. These values are minimums, not optimum values. At 80 kVp a good value to aim for is about 3.0 mm Al. You don't have to make measurements at all the different kVp values, but only at one: For example, if the HVL is greater than 2.3 mm Al measured at 80 kVp, the legality test is satisfied.

7. Collimator light field accuracy can be measured using four nickels to mark the edges of the light field or by using a specially designed test tool.
8. kVp is accurately measured using a specially designed test cassette. New electronic test devices are just beginning to appear on the market.
9. Timer accuracy can be checked by using a mechanical (spinning top) or electronic (digital readout) test tool.
10. mA linearity (or mAs reciprocity) is checked using the copper step wedge that comes with the mechanical timer or using a dosimeter to directly measure the exposure output at different mA stations.
11. Exposure reproducibility--check with a dosimeter.
12. Focal spot size--resolution slit pattern test tool or Sieman's star pattern.
13. Phototimer evaluation--use plexiglass slabs as patient equivalents.
14. Grid alignment--visual inspection or special test tool.
15. Tomographic quality control
    (a) Position of plane of focus
    (b) Cut thickness (depth of focus)
    (c) Resolving power
    (d) Uniformity of exposure over length of motion
    (e) Angle and centering of sweep
    (f) Lateral alignment of tube and cassette motion.

    Test tools are commercially available for all these tests.
16. Fluoroscopic quality control
    (a) Collimation and alignment of x-ray tube and intensifier
    (b) kVp
    (c) Focal spot size
    (d) Beam quality
    (e) Phototimer evaluation
    (f) High contrast resolution
    (g) Low contrast detectability
    (h) Exposure output

Again, several test tools are available for fluoro applications. One especially noteworthy test is for exposure output. This is usually done using various attenuators substituting for the patient, but one of the measurements is made with a lead blocker in front of the image intensifier so that the maximum possible output exposure rate of the fluoro unit can be measured. The maximum legal value is 10 R/min. (measured at the table top for under table tubes). This test is very important to insure that the patient is not needlessly overexposed during fluoroscopic examination.

There exist Federal and State codes [32, 33] which set performance standards for x-ray equipment to protect the public from unnecessary exposure to radiation. Compliance with these minimum standards at the time of equipment installation, however, is not necessarily a satisfactory indication of the equipment's capability to provide minimum patient exposure and high image quality. A well designed quality control program covers many more areas of equipment performance than the government codes, and gives accurate information on both radiation safety and image quality. Quality control tests should be performed periodically to insure continued good performance: equipment initially installed in good condition and proper calibration can deteriorate over time, and very often this deterioration is so gradual that it is only detected when a Q.C. check is made.

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