IRPA – 10
Course EO-6

SHIELDING OF DIAGNOSTIC X-RAY FACILITIES FOR COST-EFFECTIVE AND BENEFICIAL USE AND PROTECTION

by

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I. INTRODUCTION

Report No. 49 of the National Council of Radiation Protection and Measurements (1) (NCRP 49) has effectively remained the primary guide for diagnostic x-ray structural shielding design in the U.S. for more than a quarter of a century. The data and shielding methodology presented therein has served the radiology community extremely well.(2,3,4) However, many changes occurred over this period that have caused the report to become essentially obsolete.

- NCRP Report 116 (5), published in 1993, mandated substantially lower design dose limits than those given in NCRP 49.
- the diagnostic attenuation data presented is not applicable to modern three phase or constant potential equipment.
- little guidance or attenuation data is provided for shielding with materials other than lead or concrete.
- suggested typical workloads for diagnostic facilities are no longer valid in part due to the advent of high speed rare earth film/screen systems.
- the suggested use factors and occupancy factors provided in NCRP 49 are often inappropriate for today's imaging environment.
- the exposure limit for stored x-ray film has been shown to be considerably lower than necessary.
- the necessity for lead tabs to cover nails or screws in lead-lined gypsum wallboard has been questioned.
- shielding for multiple sources is not addressed.
- Report 49 does not address many of the technological developments in radiology such as computed tomography, mammography and digital imaging that have come into widespread use since its publication.

In 1990, Task Group No. 9 of the American Association of Physicists in Medicine (AAPM) Diagnostic Imaging Committee was formed with the charge to research a number of these topics and to publish updates of the data in NCRP 49. To date, six Task Group papers that are referred to later in this text, have been published or are currently in press. These provide new and more accurate estimates of the shielding parameters as well as innovative approaches for computing barrier requirements. Several of the reports also critically examine the conservatism built into the NCRP 49 methodology. The revision of Report 49 is now in progress. This paper will review new data and new concepts that will enable shielding designers to specify safe yet cost-effective barriers to diagnostic radiation.

II. NEW REQUIREMENTS

A. Design Dose Limits

A barrier interposed between the source and individual to be protected must attenuate the radiation level to the design effective dose limit. This limit represents the maximum radiation dose that a particular barrier is designed to transmit. In NCRP 49, the exposure limits selected for shielding design are 100 mR wk $^{-1}$ for occupationally exposed persons (controlled areas) and 10 mR wk $^{-1}$ for non-controlled areas. Designing a facility to these limits means that in theory, a person could receive the maximum dose limit of 5 rem (controlled areas) or 0.5 rem (non-controlled areas) over a year.

NCRP 116 recently lowered these design values significantly. Regarding occupational exposures, the report states that *"all new facilities and the introduction of new practices should be designed to limit annual exposures to individuals to a fraction of the 10 mSv per y limit implied by the cumulative dose limit"*. Currently, the fraction being suggested is one-half.

NCRP 116 also states that *" for the design of new facilities or the introduction of new practices, that the radiation protection goal in such cases should be that no member of the public would exceed the 1 mSv annual effective dose limit from all manmade sources …"*. The Table I summarizes the proposed changes in the design dose limits. These reduced values have generated controversy in the literature.(6,7)

The proposed design limits will reduce NCRP 49 levels by a factor of ten for controlled areas and by a factor of five for non-controlled areas. Shielding to these conservative dose limits using the conservative assumptions and methodology presented in NCRP 49 will obviously generate barriers thicker than those currently in use in diagnostic facilities. Based on evidence from years of film badge records, these barriers have proven to be sufficient to reduce doses to the lower levels. To avoid costly and wasteful overshielding, it is prudent to use more realistic and accurate estimates of the shielding parameters and a common sense approach to the shielding process. The following sections will examine some of these.

III. NEW DATA

A. Workload and Workload Spectra

In 1996, Simpkin(8,9) published the results of the first national survey to attempt to measure workload and use factor data. The data was primarily gathered by members of the AAPM Diagnostic X-Ray Imaging Committee Task Group No. 9. Workloads at 14 medical institutions involving approximately 2,500 patients and seven types of radiology installations were determined. The workload survey results for the workload per patient, the number of patients imaged per week and the total workload per week for each type of installation are shown in Table II. The corresponding values from NCRP 49 are also listed for comparison.

Table III lists the proposed workload values for different types of diagnostic facilities. A radiographic x-ray room typically contains a chest image receptor on one wall and a table on which overhead and cross table procedures are performed. The kVp workload distribution for the chest wall, which includes chest exams and other upright procedures, is substantially different from the workload distribution of exams performed on the table. Therefore, Table III lists workload data for the chest wall separately from the workload for the floor and other walls. Likewise, the radiographic and fluoroscopic tubes in a radiographic/ fluoroscopic room are considered separately.

NCRP reports have traditionally assumed that the entire workload in an installation is performed at a single kVp; for example; 1000 mA min wk^{-1} at 100 kVp. This conservative assumption ignores the fact that the diagnostic workload is, in fact, spread over a wide range of x-ray tube potentials. For example, in a general purpose radiographic room, extremity exams (about one third of the total exams done in the room) are normally performed at about 50-60 kVp, abdominal exams at about 70-80 kVp and chest exams at more than 100 kVp. The dose in air as well as the barrier transmission, exhibit a strong kVp dependence. For shielding design, the distribution of kVp is more important than the magnitude of the workload since the radiation level on the other side of a 1.0 mm lead barrier varies exponentially with kVp (three orders of magnitude over the range of 60-100 kVp), whereas it varies only linearly with the workload (mA min per wk). Leakage radiation shows an even more dramatic exponential decrease with kVp. From the regulatory limit of 100 mR hr^{-1} at 150 kVp, leakage rates fall by more than eight orders of magnitude over the range from 150 to 50 kVp. This significant reduction in leakage radiation with kVp is not considered in the single kVp model.

The five representative workload spectra presented by Simpkin(8) provide a new approach to the shielding design of diagnostic x-ray examination rooms. Although the actual workload distribution for a given x-ray room will vary from facility to facility and even from week to week in the same facility, the average spectra obtained from the survey represent a more realistic model than the single kVp approximation. A “kVp distribution” of workloads provides a more accurate estimate of the quality and quantity of radiation produced in a diagnostic x-ray room. Furthermore, a multiple kVp distribution produces an attenuation curve analogous to the single attenuation curve measured at a fixed kVp that is no more difficult to use than the curve from a single kVp distribution. Figure 1 compares the workload distribution for the walls and floor of a general radiographic room with the single 100 kVp ‘spike’ that results with the assumption that all exposures are made at the same kVp. Figure 2 shows the lead attenuation curve computed for that workload spectra and compares it to the attenuation curve(10) measured at 100 kVp. Figure 3 graphically compares the results of barrier thickness calculations for a general purpose radiographic room using 100 kVp with shielding requirements determined using the workload distribution.

B. Use Factors

The use factor, U, is the fraction of the primary beam workload that is directed to a particular barrier. The recommended use factors for primary barriers given in NCRP 49 are U = 1 for floors and U = _ for walls. Table IV displays the use factors that Simpkin(8) found in the AAPM survey involving 2400 patients. The survey results suggest that the primary beam is directed to the non-chest walls much less often than the fraction suggested by NCRP 49.

The proposed primary use factors suggested by the survey for a general radiographic room are given in Table V. The single kVp use factors sum to more than 1.0 which is conservative but more realistic than the NCRP 49 recommended values which sum to 2.0. There are two use factors equal to 1.0 for the workload distribution model because this model invokes two different workload spectra to shield a radiographic room. The Chest bucky distribution (that with the primary beam directed only to the chest image receptor) is separate from the Floor/other barriers distribution because the former contains higher energy components due to the higher kVp's used in chest radiography. Additionally, nearly 100% of the "over-table" workload distribution (designated Floor/other barriers) is directed to the floor, so the use factor for the floor is also assumed to be 1.0.

The wall to which the control booth abuts is normally considered a secondary barrier, so the primary use factor is usually 0.

C. Occupancy Factors

In the determination of barrier requirements, the design dose limit is weighted by the occupancy factor of the area to be protected. The occupancy factor (T) is defined as the fraction of time that a maximally present individual is present in the area while the beam is on and the barrier protecting the area is being irradiated. NCRP 49 suggests a range of from T=1 (Full) to a minimum of T=1/16 (Occasional). The NCRP 49 Rewrite Committee is proposing that a minimum value of 1/40 (one hour per week) is a more realistic value for occasional occupancy in an uncontrolled area. For example, an occupancy factor of 1/40 is suggested for an unattended waiting room and areas beyond a radiographic room door leading to a corridor. A door could be assigned an occupancy factor lower than the wall that contains it since no person will remain directly behind a door for long periods of time. However, if there is a fully occupied area beyond the low occupancy area, the former may dictate the barrier requirements despite the greater distances involved. Other suggested changes for occupancy factors will be discussed in more detail in the next presentation.

D. Pre-shielding Materials

NCRP 49 makes the assumption that the raw or unattenuated primary beam is incident on the floor or walls which constitute primary barriers. In fact, the primary beam is normally attenuated by the patient and image receptor hardware including the cassette, grid, and radiographic table or wall mounted cassette holder. Dixon(11) has shown that these structures provide significant attenuation of the primary beam. For cross table exposures, the patient, grid and cassette intercept the vast majority of the primary beam. Dixon takes the conservative approach of ignoring the attenuation provided by the patient and considers only the attenuation capacity of the hardware that intercepts the primary beam. Table VI displays his data for the equivalent thicknesses of preshielding, materials, designated x_{pre}, which is essentially independent of kVp workload spectra.

The net structural barrier required is determined by subtracting x_{pre} from the computed primary barrier thickness obtained by assuming that the raw primary beam impinges directly on the barrier.

E. Attenuation Data and Mathematical Modeling

The lead and concrete diagnostic x-ray attenuation curves provided in NCRP 49 were generated at least a quarter century ago using single-phase x-ray equipment and various measurement techniques. The revised report will utilize more current data. The set of measurements of Archer et al (10) will be assumed to represent primary broad beam attenuation of diagnostic x-rays from modern equipment operated between 50 and 150 kVp. This study utilized the calibrated x-ray and monitoring equipment at the Center for Devices and Radiological Health (United States Food and Drug Administration, Rockville, MD) to determine the transmission characteristics of lead, steel, plate glass, gypsum wallboard, lead acrylic and wood barriers. For concrete, the primary transmission data of Legare et al(12) will be employed for techniques above 40 kVp. In the mammographic energy range (25 - 35 kVp), transmission values of Simpkin(13) will be used.

To simplify the presentation of transmission data, the mathematical model published by Archer, Thornby and Bushong(14) may be used. This model, which allows parameterization of transmission data, **B** of any attenuating material, has the form:

$$\mathbf{B^*} = [\,(1 + \beta / \alpha)\exp(\alpha\,\Gamma\,x) - \beta / \alpha]^{-1/\Gamma} \qquad (1)$$

where the asterisk designates the model, x is the thickness of shielding material and alpha, beta and gamma are fitted parameters determined from transmission curves by non- linear least squares techniques. The broad beam transmission of an x-ray beam through a shielding barrier is defined as the shielded air kerma rate divided by the unshielded air kerma rate at a fixed distance. Parameter values due to Simpkin(15) that fit three phase transmission data for tungsten-anode (Al filtered) and mammography range x-ray beams at discrete kVp's for a variety of shielding materials are shown in Table VII. The data from the sources listed above have been extrapolated and interpolated in reference (15) to provide transmission curves at 5 kVp intervals required for use with the workload spectra. Table 1 also shows the primary beam dose rate per workload (mGy per mA min) at 1m, D_0^1(kVp) determined in each study. Equation (1) can also be explicitly solved for the required barrier thickness:

$$x = (1 / \alpha\,\Gamma)\ \ln\{[(\mathbf{B}^*)^{-\Gamma} + \beta/\alpha] / (1+\beta/\alpha)\} \qquad (2)$$

F. Primary Barriers

Primary barrier shielding methodology requires the knowledge of the values of six basic parameters in order to perform calculations. These parameters are:

P	The level in mSv to which radiation exposure in an adjacent occupied area must be reduced
d_p	Distance in meters from source to area being protected
W	Workload or Workload Distribution expressed in mA min per wk
U	Use Factor: the percentage of time the source of radiation is incident on the barrier
T	Occupancy Factor: the percentage of time the area is occupied
kVp	The operating potential(s) of the x-ray producing equipment at which the workload is performed in the room.

The approach to the calculation of primary barriers is as follows the methodology introduced by Dixon and Simpkin(16):

a. The unattenuated primary weekly primary dose, $D_p(kVp)$, from a source due to Workload $W(kVp)$ of this x-ray tube at this potential is

$$D_p(kVp) = D_0^1 W(kVp)\ . \qquad (3)$$

b. At a distance d_p, in m, the unattenuated primary dose is

$$D_p(kVp) = D_0^1 W(kVp) / d_p^2 \quad . \qquad (4)$$

c. If the occupied area is shielded by a barrier of a given material and thickness x having primary transmission $B_p(x, kVp)$, then the dose to the occupied area is

$$D_p(kVp) = B_p(x, kVp)\ \{D_0^1 W(kVp) / d_p^2\}.$$

(5)

d. If the workload of this tube is distributed so that a fraction of its workload is directed toward a specified barrier, then the attenuated primary dose to the occupied area behind this barrier is reduced by U.

$$D_p(kVp) = B_p(x, kVp)\ \{D_0^1\ U\ W(kVp) / d_p^2\}. \qquad (6)$$

e. For an acceptable barrier thickness, x_{acc}, the primary dose $D_p(kVp)$ at d_p must be reduced to P/T . Thus,

$$P/T = B_p(x, kVp)\ \{D_0^1\ U\ W(kVp) / d_p^2\}. \qquad (7)$$

f. Hence, the primary transmission is given by

$$B_p(x_{acc}, kVp) = \{ (P\ d_p^2) / (D_0^1\ U\ T\ W(kVp)) \}. \qquad (8)$$

This equation is essentially the same as the primary beam equation given in NCRP 49. The required barrier thickness of any material can be readily calculated by equating B_p to B* and solving Equation (1) for x_{acc} :

$$x_{acc} = (1/\ \alpha\,\Gamma)\ \ln\{[((D_0^1\ U\ T\ W(kVp)) / P\ d_p^2)^{\Gamma} + \beta/\alpha] / (1+\beta/\alpha)\} \qquad (9)$$

This equation or the graphical transmission data and equation (8) may be used to determine the required shielding thickness for any primary barrier.

Example:

Calculate the barrier requirements for the cross table wall of a busy general radiographic room adjoining a noncontrolled area with full occupancy. Assume d_p = 2.1 m .

a. **<u>NCRP 49 Method</u>:**

Using the NCRP 49 attenuation data and recommendations of W = 1000 mA-min per wk, U = _, T=1, the new dose limit of P = 0.02 mSv (0.002 R) per wk, and assuming all exposures are made at 100 kVp, the required barrier thickness is 2.6 mm Pb (commercially available as 1/8 in. or 8 lbs per sq ft).

b. **<u>Fixed kVp / New Data</u>:**

Assume all exposures are made at 100 kVp.

Also assume:

P = 0.02 mSv per wk,
U = 0.1,
T =1
W(100) = 250 mA-min per wk (from Table III, Radiographic).

The parameters found from Table VII for lead are:

D_0^1 = 4.7220 mGy per mA-min,
$\alpha = 2.500$, $\beta = 15.280$, and $\Gamma = 0.7557$.

Substituting these values into equation (9)

$$x_{acc} = \frac{1}{(2.5)(0.7557)} \ln \left\{ \frac{(4.722)(0.1)(1)(250)/(0.02)\left(2.1^{2}\right)^{0.7557} + (15.28/2.5)}{1 + (15.28/2.5)} \right\}$$

yields: x_{acc} = 1.9 mm Pb (5/64 in. or 5 lbs per sq ft).

The required shielding can also be determined graphically from equation (8) and Figure 2. The primary beam transmission required is 7.4 x 10^{-4}. From the top curve in Fig 2, the thickness of lead required is also found to be about 1.8 mm Pb.

Allowing for pre-shielding, the required barrier thickness becomes:

$x_{acc} - x_{pre}$ = 1.9 mm Pb - 0.3mm Pb = 1.6 mm Pb
(1/16 in. or 4 lbs per sq ft)

c. **Workload Spectra / New Data:**

Use the same assumptions as in the fixed kVp example above with the appropriate fitting parameters for the workload distribution "rad-floor/other barriers" for Pb. in Table VII. Assume W(distribution) = 250 mA min per wk and D_0^1 = 5.15 mGy per mA-min. The parameter values are $\alpha = 2.828$, $\beta = 18.389$, and $\Gamma = 0.5194$. Substituting these values into equation (9), we find that

x_{acc} = 1.3 mm Pb (7/128 in. or 3.5 lbs per sq ft).

The required shielding can again be determined graphically from equation (8) and Figure 2. The primary beam transmission required is 6.9 x 10^{-4}. From the lower curve in Fig 2, the thickness of lead required can be seen to be about 1.3 mm Pb

Allowing for pre-shielding, the required barrier thickness becomes

$x_{acc} - x_{pre}$ = 1.3 mm Pb - 0.3 mm Pb = 1.0 mm Pb
(5/128 in. or 2.5 lbs per sq ft).

The following paper in this symposium will discuss the calculation of primary and secondary barriers using the concept of the workload spectra in more detail.

G. Secondary Barriers

Simpkin and Dixon(17) have revised the NCRP 49 theory for calculation of secondary barriers using the new schema described above. This discussion will describe the work presented in their manuscript. The total radiation dose behind a secondary barrier, D_{sec} is the sum of leakage radiation from the x-ray tube and scatter radiation from the patient and imaging hardware.

1. Leakage radiation

Leakage radiation is limited by regulation to 0.1 R h^{-1} at 1 m at the maximum kVp and mA that the tube can be operated continuously. For radiographic tubes this is typically 150 kVp at 3 - 5 mA. The amount of shielding required in the housing to limit transmission to the regulatory limit is based on these techniques even though typically the tube is rarely, if ever operated at 150 kVp. The radiation that is transmitted through the housing is much more penetrating than the primary or scattered radiation and is therefore characterized by the half value layer (HVL) in a material at high attenuation. Simpkin has determined the updated the high attenuation HVL values of leakage radiation.

The NCRP 49 model for leakage greatly overestimates both the unshielded and shielded leakage doses because the leakage technique factors do not approximate clinically used techniques. Assuming leakage factors of 150 kVp at 3.3 mA, and typical clinical techniques in the 60 - 100 kVp range, the NCRP 49 model over-predicts the unshielded leakage dose factors by 10^6 at 60 kVp, 250 at 80 kVp and 4.5 at 100 kVp. The NCRP 49 model results in leakage factors about 20 times greater than those predicted by the workload distribution model for radiographic tubes. Even larger disparity is found for leakage doses behind typical shielded barriers. These differences are due to the far greater transmission of radiation at the leakage technique factor as compared to that at typical clinical kVp's

2. Scatter Radiation

The NCRP equation for scatter uses the scatter fraction values taken from the work of Trout and Kelley(18). However, Dixon(11) showed that these 50 and 70 kVp data, taken with lightly filtered beams, underestimate scatter from modern units by a factor of 2. This new data will be incorporated into the revised NCRP Report.

The NCRP 49 scatter equation also inaccurately assumes that the entire clinical workload is performed at a single kVp. When the workload distribution concept is utilized to determine the doses due to scatter radiation, it is found that the unshielded scatter dose is lower than that generated by the NCRP model. This is due to the decreased x-ray tube outputs at the lower kVp values of the workload distribution and the reduction of scatter factors with lower kVp. The shielded scatter factor is likewise found to be lower due to the reduced transmission of the workload distribution at the lower kVp's that are used clinically.

3. Secondary Barriers

The secondary barrier of thickness x_{acc}, must attenuate the total radiation dose, which is the sum of the leakage and scatter doses, to the permissible dose limit P. Simpkin and Dixon(17) have determined the "exact" secondary barrier shielding requirements by numerically computing the secondary transmission through a variety of shielding materials. This value of x_{acc} represents the thickness of shielding required to make the sum of the calculated leakage and scatter exposures equal to the design maximum exposure.

The direct solution of this equation eliminates the need to use the overly conservative "add one HVL" approximation recommended in NCRP 49.

The workload spectra has also been incorporated into the methodology to obtain realistic shielding requirements for each type of room that requires secondary barriers, including interventional laboratories, fluoroscopy, mammography and computed tomography.

H. Protection for X-Ray Film

NCRP 49 recommends that shielding for radiographic film limit the exposure to the film to 0.2 mR per storage period. However, this recommendation was based on film emulsions containing more silver than current emulsions. Modern x-ray film is much less sensitive to ionizing radiation. Suleiman et al(19) have shown that with typical modern x-ray films, radiation levels of from about 50 to 300 times greater than the NCRP 49 limit are required to produce fog levels of 0.05 optical density. Based on these studies, the NCRP Rewrite Committee will propose a new limit for the exposure of medical x-ray film, namely 0.1 mGy (10 mR) per storage period. If a storage period of one month is assumed, then the limit will become 0.025 mGy per week.

Figure 4 exhibits relative differences in the shielding required for radiographic film using the different methods. The primary barrier thickness given in NCRP 49 Appendix C, Table 6, at a distance of 2.1 m is 3.7 mm (5/32 in or 10 lb) Pb. or 29 cm (11.4 in) of concrete (a bomb shelter!). Computations using the revised parameter values and a fixed 100 kVp workload or the workload spectra methodology, result in much more reasonable barriers to shield the films of today.

The Suleiman study points out that unexposed x-ray film loaded into a cassette is about 100 times more sensitive to fogging from radiation than film not in a cassette. Thus, in-room areas where loaded cassettes are stored, such as inside the passbox or behind the control booth may require special consideration.

H. Lead Disks to Cover Drywall Screws

Shearer et al and Gray have evaluated the practice of using lead discs or tabs to cover the drywall screws or nails used to attach lead-bonded sheetrock to facility walls. They found that only very small perforations in the sheet lead are made when the screw is inserted normally and that the attenuation of the screw compensates for the lead removed. However, if lead disks are used, the screw is often pounded into the wall with a hammer and an indention in the drywall is made so the disc can be glued flush with the wall surface. This process causes a major breech in the integrity of the lead sheet. Both studies concluded that the only time that lead disks are required is when the surface is prepared to receive the lead disks.

I. Evaluation of Shielding Adequacy

The final steps in the shielding process involve the acceptance test of the shielded x-ray facility. In addition to verifying that the required thickness of shielding materials were used, the survey should determine if there are voids in the barriers due to improper construction techniques. Common reasons for voids include mispositioning of leaded gypsum wallboard (upside down or wrong barrier), misaligning shielding sections and removal of shielding for plumbing or electrical without installing compensatory backing material.

Hubbard(20) has produced a detailed, step by step explanation of the role of the qualified expert in the acceptance testing of a diagnostic x-ray facility that will be included in the NCRP 49 Rewrite document.

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TABLES

Table I. Comparison of design dose limits.

	NCRP 49	PROPOSED
Controlled Area	100 mR per wk (~1.0 mSv per wk)	0.1 mSv per wk
Non-Controlled Area	10 mR per wk (~ 0.1 mSv per wk)	0.02 mSv per wk

Table II. Comparison of workload values for a diagnostic facility. Values presented under Simpkin are the mean values from the survey.

Room Type	**Workload per patient (mA min patient^{-1})**		**No. patients per week**		**Total Workload (mA min week^{-1})**	
	Simpkin	**NCRP 49 100 kVp**	**Simpkin**	**NCRP 49 100 kVp**	**Simpkin**	**NCRP 49 100 kVp**
General Radiographic room	2.45	8.3	112	120	274	1000
Fluoroscopic Tube (R&F)[a]	12.9	6.25	17.6	120	227	750
Radiographic Tube (R&F)[a]	1.51	---	23.3	---	35	---
Dedicated Chest room,	0.216	0.5	206	300	44	150
Mammographic suite	6.69	---	47.4	---	317	---
Cardiac Angiographic suite	160	---	19.1	---	3050	---
Peripheral Angiographic suite.	64.1	17.5	21	40	1350	700
Computed Tomography[b]	200	---	100	---	20000	---

[a] R & F is a general purpose fluoroscopic room with separate radiographic x-ray tube

[b] estimated, depends on the type of scanner

Table III Proposed values for workloads

*****NOT FINAL-FOR DISCUSSION ONLY***

(These values are for shielding a person beyond a barrier during an eight hour day.)

Room Type	Workload per patient (mA min patient^{-1})	No. patients per week Facility Type		Total Workload (mA min week^{-1}) Facility Type	
		Average	**Busy**	**Average**	**Busy**
Radiographic (chest bucky)	0.6	120	160	75	100
Radiographic (Floor/oth barriers)	2.0	75	120	150	250
Dedicated Chest room	0.3	200	400	60	120
Fluoroscopic Tube (R&F)	13	20	30	250	400
Radiographic Tube (R&F)	1.5	20	40	30	60
Mammographic suite	7	50	100	350	700
Cardiac Angiographic suite	160	20	30	3200	4800
Peripheral Angiographic suite.	65	20	30	1300	2000
Computed Tomography	200	60	100	12000	20000

Table IV. Primary beam use factors determined in the AAPM Task Group No. 9 study. A zero value indicates that the primary beam is intercepted by a beam stop such as an image intensifier or shielded cassette holder in mammography. In the radiographic room, Wall #1 holds the upright chest image receptor and Wall # 2 is the cross table lateral wall.

Room Type	Primary Barriers		
	Floor	**Wall #2**	**Wall #3**
General Radiographic room	0.69	0.065	0.016
Fluoroscopic Tube (R&F)	0	0	0
Dedicated Chest room	0	0	0
Mammographic suite	0	0	0
Cardiac Angiographic suite	0	0	0

Peripheral Angiographic suite	0	0	0

Table V. Proposed primary use factors for the workload distribution models.

Barrier	**USE FACTOR (Single kVp)**	**USE FACTOR (Workload Distribution)**
Floor	0.70	1.00 (Floor/other barriers)
Wall # 1 (Chest image receptor)	0.25	1.00 (Chest Bucky)
Wall # 2 (Cross Table)	0.10	0.10 (Floor/other barriers)
Wall # 3	0.05	0.05 (Floor/other barriers)
Wall # 4 (Control Booth Wall)	Normally 0 (Secondary)	Normally 0 (Secondary)

Table VI. Equivalent thickness of primary beam preshielding (x_{pre}) which may be used with any workload spectra or with fixed potentials of 100 kVp or less.
Row A: Values for radiographic table and associated image receptor hardware. These values may also be used for a wall mounted image receptor.
Row B: Values for cross table lateral exposures attenuated by grid and cassette.

Application	**Lead**	**Concrete**	**Steel**	**Plate Glass**	**Gypsum**
A	0.85 mm	72 mm	7.0 mm	83 mm	230 mm
B	0.3 mm	30 mm	2 mm	35 mm	90 mm

Table VII. Parameters for fit of selected primary beam transmission curves using Equation (1). The 35 kVp and mammography data is for Mo-anode x-ray tubes. All other data is for W-anode tubes. All thicknesses are in millimeters of material.

Material	Energy	Alpha	Beta	Gamma	D_0[1]
Lead	***Single kVp***				
	35	29.55	164.7	0.3948	0.064
	100	2.500	15.28	0.7557	4.722
	125	2.219	7.923	0.5386	7.170
	Workload Distribution				
	Rad/floor-other barriers	2.828	18.389	0.5194	5.15
	Rad/chest bucky	2.2997	13.406	0.5774	2.25
	Chest room	2.2874	10.784	0.6404	1.21
Concrete	***Single kVp***				
	35	0.2528	1.807	0.4648	0.064
	100	0.03925	0.08567	0.4273	4.722
	125	0.03502	0.07113	0.6974	7.170
	Workload Distribution				
	Rad/floor-other barriers	0.03993	0.1448	0.4231	5.15
	Rad/chest bucky	0.03552	0.1177	0.6007	2.25
	Chest room	0.03622	0.07766	0.5404	1.21
Steel	***Single kVp***				
	35	5.716	43.41	0.4857	0.064
	100	0.3415	2.420	0.7645	4.722
	125	0.2130	1.677	0.8217	7.170
	Workload Distribution				
	Rad/floor-other barriers	0.2535	2.740	0.4297	5.15
	Rad/chest bucky	0.2179	2.677	0.7206	2.25
	Chest room	0.2501	1.989	0.7721	1.21

FIGURE LEGENDS

Figure 1. Comparison of mean workload per patient as a function of operating potential as determined in the AAPM Diagnostic Imaging Task Group 9 survey with the (truncated) per patient workload determined by assuming that the entire workload is performed at 100 kVp. The workload distribution shown is for Rad room- floor/other barriers which includes the portion of the workload directed at the floor and walls other than the chest wall. The distribution for the chest wall will be skewed toward higher kVp's because of the higher potentials employed in chest imaging.

Figure 2. The fixed kVp and the workload distribution reproduced in Figure 1 each generate transmission curves through a variety of shielding materials. The 100 kVp lead curve was measured as described in reference (10). The transmission curve for the distribution was determined by computing the transmission of the incremental dose in each kVp interval through a given thickness of lead and summing the resulting transmission over all kVp values.

Figure 3. Ratio of the barrier thickness (after Simpkin(9)) required for primary and secondary barriers in a general radiographic room; 100 kVp : Workload Distribution. The graph shows the ratio of the requirements of the unrealistically conservative 100 kVp model to the workload distribution which more accurately approximates clinical usage.

Figure 4. Relative barrier thickness required for the shielding of radiographic film at 2.1 meters from the source for a period of one month. The fixed 100 kVp and workload spectra models use the revised parameter values described in the text.