Paper

THE ESTIMATION OF OCCUPATIONAL EFFECTIVE DOSE IN DIAGNOSTIC RADIOLOGY WITH TWO DOSIMETERS

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Abstract—**Annual effective dose limits have been proposed by national and international radiation protection committees. Radiation protection agencies must decide upon a method of converting the radiation dose measured from dosimeters to an estimate of effective dose. A proposed method for the estimation of effective dose from the radiation dose to two dosimeters is presented. Correction factors are applied to an over-apron collar dose and an under-apron dose to estimate the effective dose. Correction factors are suggested for two cases, both with and without a thyroid shield. Effective dose may be estimated by the under-apron dose plus 6% of the over-collar dose if a thyroid shield is not worn or plus 2% of the over-collar dose if a thyroid shield is worn. This method provides a reasonable estimate of effective dose that is independent of lead apron thickness and accounts for the use of a thyroid shield.**
Health Phys. 67(6):611–615; 1994

Key words: dosimetry; exposure, occupational; radiation, ionizing; radiation protection

INTRODUCTION

FLUOROSCOPY PROCEDURES are the largest source of occupational radiation dose in medicine. In general radiography, fluoroscopic and special procedures may account for 90% of the total collective dose (NCRP 1990). The radiation dose to personnel performing these procedures is non-uniform, with relatively high doses to the head, neck, and extremities; and much lower doses to the trunk and other regions protected by shielding. All personnel in a fluoroscopic procedure room are required to wear lead aprons during a fluoroscopic exam.

The International Commission on Radiological Protection (ICRP) has developed the concept of effective dose to relate the risk from a partial or non-uniform exposure to the risk from an equivalent whole body exposure (ICRP 1991). Annual effective dose limits have been proposed by the National Council on Radiation Protection and Measurements (1993) and the ICRP (1991).

Effective dose may be calculated using an equation suggested by the ICRP:

$$E = \sum_T w_T \cdot H_T \quad (1)$$

where w_T is the tissue weighting factor and H_T is the equivalent dose to tissue T (ICRP 1991). For x rays, the equivalent dose is equal to the absorbed dose, since the radiation weighting factor for x rays is 1. The tissue weighting factors from the ICRP are shown in Table 1. The tissues and organs in Table 1 are grouped according to the degree of shielding provided by lead aprons. Typical lead aprons used in medical fluoroscopy have attenuation approximately equal to an equivalent lead thickness of 0.5 mm although lead aprons are available from 0.25 mm to 1.0 mm equivalent lead thickness. For x-ray energies typically encountered in fluoroscopy of 70 to 100 peak kilovoltage the transmission of a 0.5-mm lead apron would be 0.5% to 3.5% (NCRP 1976). In addition to lead aprons, shielding used in medical fluoroscopy includes thyroid shields, movable transparent lead shields, and lead drapes. The use of these shielding devices is variable and depends both on the type of procedure and individual preference.

Although the need for multiple dosimeters in personnel dosimetry has been recognized, the dosimeter value with the highest measured dose typically has been recorded as a whole body dose (Hudson 1984; Reece et al. 1985). This may result in a large overestimation of effective dose.

Current personnel dosimetry methods are not adequate for estimating effective dose during fluoroscopic procedures. This paper will review methods for estimating occupational effective dose in medical fluoroscopy and propose a method based on applying weighting factors to an over-collar and under-apron dose.

REVIEW OF PREVIOUS METHODS

Three methods have been used to calculate effective dose or effective dose equivalent (EDE) from dosimeter readings (Faulkner et al. 1988, 1993; Gill et al. 1980; Webster 1989; Niklason et al. 1993). Effective

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(*Manuscript received* 10 *January* 1994; *revised manuscript* 17 *May* 1994, *accepted* 12 *July* 1994)

0017-9078/94/$3.00/0

Table 1. The ICRP tissue weighting factors (ICRP 1991) and the shielding of tissues by lead aprons.

	Tissues with weighting factors			
	0.20	0.12	0.05	0.01
Shielded	Gonads	Colon Lung Stomach	Bladder Breast Liver	
Partially Shielded		Red Bone Marrow	Esophagus Remainder	Skin Bone
Not Shielded			Thyroid	

dose equivalent was used to estimate whole body dose before the adoption of the term effective dose. The EDE was based on weighting factors for only six organs and had a remainder weighting factor of 0.3 (ICRP 1977).

Two methods have been proposed for personnel dosimetry which include the application of a correction factor for a single dosimeter measurement (Faulkner et al. 1988 and 1993) or the use of correction factors for the doses from two dosimeters (Gill et al. 1980; Webster 1989). The third method involves calculating tissue or organ dose and applying the tissue weighting factors listed in Table 1. This method has not been used by radiation protection agencies because of the difficulty in calculating organ dose. This dffficulty is associated with the variability of the angle of incidence of scattered radiation (Piltingsrud et al. 1992), the energy of the scattered radiation, the types of shielding used and the size of the individual.

Correction values of one-fifth or one-third of the over-collar dose have been discussed by radiation protection agencies to estimate effective dose. Faulkner et al. (1993) suggest the effective dose for a radiologist wearing a 0.5 mm apron, using a beam energy of 90 kVp, and an undertable tube may be estimated by dividing the collar dose by 32. Our previous study suggests the correction factors for the over-collar dose depend upon the use of a thyroid shield and were approximately 25 and 11, with and without a thyroid shield, respectively (Niklason et al. 1993).

Methods based on weighting factors applied to the dose from two dosimeters have been suggested by Gill et al. (1980) and Webster (1989). Both of these methods were developed before the adoption of the term effective dose and use effective dose equivalent (EDE). Gill et al. have proposed using the following equation to calculate *EDE*:

$$\mathrm{EDE} \approx 0.6 \cdot H_u + 0.4 \cdot H_o \qquad (2)$$

where H_u is the under-apron dose equivalent, and H_o is the over-apron dose equivalent. Webster (1989) proposed another equation based on an earlier study by Faulkner et al. (1988):

$$\mathrm{EDE} \approx 1.5 \cdot H_u + 0.04 \cdot H_o. \qquad (3)$$

PROPOSED METHOD

The use of methods described previously in the estimation of effective dose will result in substantial errors because of the different weighting factors associated with EDE (Huda et al. 1991) and because the use of thyroid shields are not considered in any of the proposed methods. The use of thyroid shields may reduce effective dose by at least a factor of two (Niklason et al. 1993). Several methods described previously are based on the use of correction factors for a single dosimeter. These methods will result in significant errors because when a correction factor is applied to an over-collar dose, an estimation of the lead apron attenuation must be made. Apron attenuation is a function of x-ray energy, lead apron thickness, and imaging geometry. It is difficult to estimate all three factors. Large errors may also result from a correction factor applied to an under-apron dose because head, neck, and extremity dose must be estimated. The method presented in this study, will provide an accurate estimation of effective dose and provide a correction for the use of thyroid shields.

The proposed method described for calculating effective dose from dosimeter measurements emerges from a study of occupational effective dose to interventional radiologists (Niklason et al. 1993). The effective dose is calculated using an over-apron collar dose and an under-apron waist dose. The proposed model is based on the following:

1 the under-apron dose is assumed to be a whole body dose;
2 the head and neck effective dose are calculated using organ dose tables (Wall et al. 1988), depth dose tables (Harrison 1981), and the collar dosimeter measurements;
3 the extremity effective dose is estimated from depth dose tables (Harrison 1981) and the collar dosimetry to complete the estimation of effective dose.

APPROACH

The method proposed for the estimation of effective dose is based on the correction factors shown in Table 2 for the over-collar dose and the use of an under-apron dose as a whole body dose. The derivation of the correction factors is presented in the appendix. The following equations are proposed as a method for estimating effective dose from two dosimeters:

$$\mathrm{E} = 0.06\,(H_{os} - H_u) + H_u \quad \text{without a thyroid shield} \qquad (4)$$

$$\mathrm{E} = 0.02\,(H_{os} - H_u) + H_u \quad \text{with a thyroid shield.} \qquad (5)$$

The same terminology as used above is applied to these equations, however, the shallow dose (H_{os}) rather than the deep dose is used for the over-collar dose. The shallow dose is more appropriate when organ dose tables and depth dose tables are used for dose calculation because these tables are based on

Table 2. Correction and weighting factors for effective dose calculations of the head, neck, and extremities.

Organ or tissue	Weighting factor	Tissue dose/entrance dose		E/collar dose[a]
		Head and neck	Extremities	Total
Red Bone Marrow	0.12	0.017 (0.011, 0.024)	0.010 (0.004, 0.023)	0.0032 (0.0018, 0.0056)
Bone Surfaces	0.01	0.100 (0.008, 0.116)	0.600 (0.236, 1.287)	0.0070 (0.0024, 0.0140)
Skin	0.01	0.050 (0.047, 0.065)	0.370 (0.185, 0.740)	0.0042 (0.0023, 0.0081)
Thyroid	0.05	0.794 (0.667, 0.884)		0.0397 (0.0334, 0.0442)
Esophagus	0.05	0.100 (0.080, 0.110)		0.0050 (0.0040, 0.0055)
Total CF with thyroid shield[b]				0.0144 (0.0065, 0.0277)
Total CF without thyroid shield				0.0591 (0.0439, 0.0774)

[a] E/collar dose is the correction factor (CF) which would be applied to convert the collar dose to effective dose. The correction factors shown are typical values. The first numbers in parentheses are calculated assuming a low-dose scenario while the second number in parentheses are calculated using a high-dose scenario as discussed in the text.
[b] It is assumed that the thyroid and esophagus are shielded by a thyroid shield.

skin entrance dose rather than the dose at a depth of 1 cm. The weighting factor for the under-apron dose is unity because this badge is assumed to be a whole body dose. Because the under-apron dose is applied to the whole body, this dose is subtracted from the over-collar dose before a correction is made for the over-collar dose. Since the under-apron dose is typically only a few percent of the over-collar dose, the equation may be further simplified to 6% of the over-collar shallow dose plus the under-apron dose for an individual who does not use a thyroid shield. For an individual wearing a thyroid shield, the simplified equation would be 2% of the over-collar dose plus the under-apron dose.

RESULTS AND DISCUSSION

Comparison of methods for effective dose estimation

The effective doses calculated from the methods described are shown in Table 3. The predicted annual over-collar and under-apron dose to the 28 radiologists from our previous study were used to calculate the effective dose by each method (Niklason et al. 1993). The predicted average annual dose for the 28 radiologists was 0.88 mSv under-apron (deep dose), 48 mSv over-collar (deep dose), and 55 mSv over-collar (shallow dose). Deep doses were used for all effective dose calculations, except for calculations with the proposed method in which shallow doses to the over-collar dosimeter were used.

Table 3. Comparison of methods for the estimation of effective dose.

Method	Mean E (mSv)[a]	
	With thyroid shield	Without thyroid shield
$H_o/3$	16	16
$H_o/5$	9.6	9.6
$H_o/25$ or 11	1.9	4.4
Faulkner (1993)-$H_o/32$	1.5	1.5
Gill (1980) (EDE)	20	20
Webster (1989) (EDE)	3.2	3.2
Proposed	2.0	4.1

[a] The mean effective dose (E) or effective dose equivalent (EDE) for each model using the over-collar and under-apron dosimetry from the study of 28 interventional radiologists (Niklason et al. 1993). H_o is the over-collar dose equivalent.

The results from the methods vary by more than an order of magnitude as shown in Table 3. It is assumed that studies based on organ dose calculation are the most accurate. This assumption is based on the definition of effective dose which requires an organ dose for each of the organs and tissues listed in Table 1. The two methods of calculating effective dose which are based on organ dose calculations are the proposed method and the method of Faulkner et al. (1993).

For imaging conditions similar to those encountered in the interventional dose study, Faulkner et al. (1993) proposed dividing the over-collar dose by a factor of 32. This method resulted in the lowest estimate of effective dose as shown in Table 1. Faulkner et al. did not account for the use of a thyroid shield and concluded that the use of a single dosimeter dose cannot provide an accurate estimate of effective dose for all conditions. Proposed methods based on dividing the over-collar dose by 3 or 5 will result in significant overestimation of effective dose.

The use of two badges allows dose to be measured from both regions and has the potential to provide a more accurate estimation of effective dose under a variety of conditions. The proposed method is designed to calculate effective dose from two dosimeters and is the only method at present which will account for the use of a thyroid shield. For individuals without thyroid shields, the proposed method results in an estimate of effective dose which is 2.7 times higher than the method of Faulkner et al. (1993).

Potential sources of error with the proposed method

A listing of potential sources of errors may be obtained by analyzing the assumptions upon which the proposed method is based. First, the assumption that the under-apron dose is a whole body dose will result in an overestimation of effective dose because no tissue attenuation is assumed. However, it is a conservative and simple method. In addition, some lead

aprons have reduced lead thickness on the side compared to the front. Therefore, applying a simple correction for tissue attenuation may underestimate the actual organ dose.

Second, the dose to the head was calculated from the collar dose. Most of the head receives less radiation than that measured by the collar dosimeter because of increased distance from the patient. Given an assumed beam energy of 80 kVp with 3 mm of aluminum beam filtration, and that the majority of fluoroscopic exams are at 80 kVp or less, this would represent an overestimation of absorbed dose in many situations.

Third, the calculation of effective dose from exposure to the extremities was based on the dose to skin, bones, and red bone marrow, as estimated from the over-collar dose. No tissue attenuation was assumed in the estimation of skin dose, which results in an overestimation. Although portions of the hands, forearms, and legs may receive higher dose than the collar dosimeter for some types of procedures, other regions of the extremities may be shielded by the body, apron, table, or other shielding devices and receive less radiation dose than the collar dosimeter. The dose to the extremities may vary widely depending upon the type of procedure and the shielding used. However, although the effective dose to the extremities is more difficult to estimate than other regions, skin and bone have very low tissue weighting factors of 0.01. As a result, variation in the dose to the hands, forearms, or lower legs has little impact on total body effective dose. The red bone marrow in the extremities, which has a higher tissue weighting factor, is in the upper humerus and probably receives a radiation dose close to that of the collar dosimeter.

The potential for underestimation of effective dose may be examined by using a high-dose scenario. Using the proposed method, the high- dose scenario is based on assumptions which would result in the largest underestimation of effective dose for conditions which may be encountered in medical fluoroscopy. These assumptions include: the fluoroscopy kVp is 110 with 3 mm of aluminum filtration (highest beam energy typically used in fluoroscopy); and the average dose to the extremities is two times the dose to the over-collar dosimeter. In this case, the correction factors shown in parentheses in Table 2 are 3% and 8%, as compared to 2% and 6%, respectively. The mean effective dose for the 28 radiologists would be 28% higher with the use of a thyroid shields and 26% higher without thyroid shields than that calculated using eqn 4 and eqn 5.

A low-dose scenario may also be postulated to examine the potential for overestimation of effective dose from factors such as the x-ray beam energy and extremity dose estimation. This low-dose scenario assumes: the fluoroscopy kVp is 60 with 2 mm of aluminum filtration; and the average dose to the extremities is one-half the dose to the collar dosimeter. For this scenario, the correction factors shown in parenthesis in Table 2 for the over-collar dose are 0.7% with a thyroid shield and 4.5% without a shield. These correction factors would result in an effective dose estimation that is 36% lower with the use of a thyroid shield and 20% lower without a thyroid shield than the effective dose estimations using eqn 4 and eqn 5.

CONCLUSIONS

Radiation protection agencies will require an estimate of effective dose to determine compliance with annual effective dose limitations. If a simple model, such as dividing the over-collar dose by a factor of three or five, is chosen the effective dose may be substantially overestimated. There is the possibility that an individual may appear to exceed the annual effective dose limits when the individual, in fact, has not.

The analysis of the proposed model is based on dosimetry for interventional radiologists. Personnel performing other types of fluoroscopic procedures typically receive less radiation dose and may use different beam energies, shielding, or imaging geometry than interventional radiologists. However, the proposed model and the use of two dosimeters, one to measure the dose transmitted through the lead apron and another to sample the dose at the neck will allow a reasonable estimate of effective dose for the range of imaging conditions typical of medical fluoroscopy.

The model presented provides a more accurate estimate of effective dose. In general, the assumptions upon which the model is based are conservative and result in slightly higher effective dose than applying a correction factor for a single collar dosimeter as suggested by Faulkner et al. (1993). However, a single correction factor cannot account for the range of imaging conditions typically encountered. An accurate estimate of effective dose is of value because it allows an accurate estimation of risk. Models based on extremely conservative assumptions are of little value if individuals cannot estimate risk or if risk estimates are inflated by overestimating effective dose.

In summary, a proposed method for calculating effective dose has been presented which results in a more accurate estimate of effective dose than previous methods. This method has two advantages over previous methods. First, the proposed method provides an estimate of effective dose which is independent of lead apron thickness. Next, this method accounts for the use of a thyroid shield which may reduce the effective dose by one-half.

Acknowledgments—The authors wish to thank Laura E. Niklason for help in manuscript organization and editing.

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APPENDIX

ORGAN DOSE in the head and neck was calculated using the organ dose tables for an anteroposterior projection of the skull and cervical spine. The cervical spine projection was required because the thyroid is only partially in the field of an anteroposterior skull projection. A beam quality of 80 kVp with filtration of 3 mm of aluminum was used. Dose to the skin of the head was not included in the dose tables and was calculated assuming 9% of the total skin surface is in the head and neck region (ICRP 1975). A depth dose of 0.55 was assumed for the skin effective dose calculation (Niklason et al. 1993). Esophageal dose was calculated using a depth dose of 0.50 and assuming 20% of the total length of the esophagus was above the lead apron.

The effective dose to the extremities was calculated using the ICRP report on the Reference Man to determine the fraction of red bone marrow, skin, and bone surfaces in the extremities (ICRP 1975). Two percent of the red bone marrow was assumed to be in the head of the humerus. The red bone marrow in the upper femur was assumed to be shielded by the lead apron. The fraction of the total body skin and bone surfaces in the extremities not shielded by the lead apron was assumed to be 37% and 39%, respectively. The red bone marrow and bone surfaces were assumed to be at an average depth of 4 cm and 2.5 cm, respectively. The higher attenuation of bone relative to soft tissue resulted in an enhancement factor of 120% used for bone absorbed dose calculations.

The over-collar dose was used to calculate the effective dose to the extremities. The correction factors used in estimating the effective dose in the head, neck, and extremities from the collar dose are shown in Table 2. The last column in Table 2 shows the correction factors for each tissue. The correction factor is calculated by multiplying the sum of the tissue dose to entrance dose ratios for the head and neck and extremities by the tissue weighting factor. The remainder effective dose for the head, neck, and extremities was calculated as 5% of the effective dose. This is equivalent to increasing the correction factors by 5%. The final correction factors for the over-collar dose, after the addition of the remainder term, may be estimated by 2% with a thyroid shield and 6% without a shield.

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