EVALUATION OF RADIATION EXPOSURES TO PERSONNEL IN FLUOROSCOPIC X-RAY FACILITIES

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Abstract—Personnel monitoring data reported in the literature at selected monitoring sites for personnel working in fluoroscopic X-ray facilities are analyzed. The results are used to attempt to more realistically estimate the potential organ doses for X-ray personnel wearing protective devices such as lead aprons and protective eyeglasses when these personnel wear only one dosimeter positioned outside the apron at the collar. The applicability of these results to current U.S. dose standards and the ICRP weighted dose equivalent concept is discussed.

INTRODUCTION

Personnel in fluoroscopic X-ray facilities wear lead rubber aprons covering the torso and, in some cases, lead glass eyeglasses and thyroid shields to protect themselves from scattered radiation from the patient. Some sensitive organs are thus wholly or partially shielded by the protective devices. Since commonly a single personnel dosimeter is worn outside the apron, at the collar or neckline location, the interpretation of the indicated exposure is complex, both in terms of applicability to existing occupational dose standards and in evaluation of potential organ doses and hence in estimating the potential biological risk. Further, although dose reduction to occupational personnel should always be pursued in observance of the ALARA philosophy, because of possible long special fluoroscopic procedures, numerous exams, and other contributing factors, the recorded personnel doses may reach levels near the maximum limit. Questions may then arise in regard to the level of exposure at the collar that may truly be an “over-exposure” and thus must be reported to the responsible agency.

We have attempted to examine personnel monitoring data reported in the literature for personnel in fluoroscopic X-ray facilities to determine potential organ doses which are extrapolated from the dosimeter worn on the collar. The potential organ doses associated with recorded exposures at the maximum permissible levels are then compared to current occupational dose standards and recommendations. The results given will assist in the interpretation of the exposure recorded at a single location by a personnel dosimeter.

REGULATIONS

In the U.S., persons must comply with occupational dose standards which have not significantly changed since their establishment in 1960. The Atomic Energy Commission (AEC, now the Nuclear Regulatory Commission) dose limits (10 CFR 20) are those which all federal and state agencies use (BRH 78, 29 CFR 1910.96) and are based on the recommendations of the Federal Radiation Council (FRC 60) (whose responsibilities were transferred to the Environmental Protection Agency in 1970) and the National Council on Radiation Protection and Measurements (NCRP58). The recommendations of the FRC did not differ substantially from the previous International Commission on Radiological Protection (ICRP) and NCRP recommendations (ICRP58; NCRP58).
Since 1960 the NCRP and ICRP have modified some of their recommendations with the ICRP adopting the most significant changes (NCRP71; ICRP77). The ICRP in ICRP Publication 26 (ICRP77) refers to specific organ weighting factors and assigns a dose limit on the basis of the summation of the weighted dose equivalents to the organs in the case of partial body irradiation. NRC and EPA have proposed changes in the present occupational dose standards recently which are expected to be more in accord with ICRP 26 (10 CRF 20, 46 CFR 7836).

Table 1 is a summary of the pertinent recommendations of each group for the various organs. For simplicity, all references to dose limits are for yearly doses, although the dose standard may actually refer to quarterly doses. Some disparities are of interest in the present regulations, i.e. in NRC regulations, the maximum permissible dose (MPD) for the thyroid is not stated nor is the MPD for “other organs”.

**ORGAN DOSES**

Personnel monitoring data reported in the literature (Ba78; Be75; Ch80; Ma72; Re78; St74; Wo71) for X-ray fluoroscopic work are summarized in Table 2 and have been analyzed for specific organs of interest. Unless otherwise stated, all references to organ doses assume no absorption occurs in overlying tissue.

(1) *Lens of eye.* The formation of radiation induced cataracts has been shown to be a non-stochastic effect, i.e. it has an apparent dose threshold. This threshold is believed to be 200–500 rad for acute exposures and about 1000 rad for chronic exposures to low-LET radiation (NAS80). Although NCRP (NCRP71) recommended a dose limit of 5 rem/yr to the lens of the eye, ICRP (ICRP80) has recommended 15 rem/yr which would appear to provide adequate protection for either acute or chronic exposures.

From Table 2, it appears that actual exposures to the eye (which may be considered to be identical to either the eye or forehead reported exposures) compared to exposures at the collar (taken as either the collar or thyroid values) range from about one-half to two times (one study) that of the collar location with the true ratio most likely about one, because of the proximity of the collar location to the eye and expected patterns of radiation fields to which personnel would be exposed. Thus, with respect to present U.S. regulations, 5 rem/yr indicated by a collar monitor would be the applicable reporting value in the absence of eye shielding. If collar monitoring results show doses approaching 5 rem/yr, then protection of the lens of the eye would be indicated, although no added measures to protect the lens of the eye would be necessary for personnel doses much less than 5 rem/yr because of the threshold effect. There are protective lead glass spectacles available that can reduce eye doses to about 15% of the unshielded dose (Ag78; Be77; Ri76). However, if the person already wears eye glasses containing glass lenses (such as photochromic or crown glass) these will be adequate for they have been shown to reduce the dose about 50%

### Table 1. Maximum permissible doses (MPD), in rem/yr, given by standards setting groups

<table>
<thead>
<tr>
<th>Organ</th>
<th>NCRP 39</th>
<th>ICRP 26</th>
<th>NRC</th>
<th>FRC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lens of eye</td>
<td>5</td>
<td>30+</td>
<td>5##</td>
<td>5</td>
</tr>
<tr>
<td>Whole body</td>
<td>5</td>
<td>5</td>
<td>5##</td>
<td>5**</td>
</tr>
<tr>
<td>Bone marrow</td>
<td>5</td>
<td>42*</td>
<td>5##</td>
<td>5</td>
</tr>
<tr>
<td>Thyroid</td>
<td>15</td>
<td>50*</td>
<td>--**</td>
<td>30</td>
</tr>
<tr>
<td>Gonads</td>
<td>5</td>
<td>20*</td>
<td>5##</td>
<td>5**</td>
</tr>
<tr>
<td>Skin</td>
<td>15</td>
<td>50*</td>
<td>30</td>
<td>30</td>
</tr>
<tr>
<td>Hands</td>
<td>75</td>
<td>50*</td>
<td>75</td>
<td>75</td>
</tr>
<tr>
<td>Feet and ankles</td>
<td>15#</td>
<td>50*</td>
<td>75</td>
<td>75</td>
</tr>
<tr>
<td>Forearms</td>
<td>30</td>
<td>50*</td>
<td>75</td>
<td>75</td>
</tr>
<tr>
<td>Lower legs</td>
<td>15#</td>
<td>50*</td>
<td>--**</td>
<td>15</td>
</tr>
<tr>
<td>Other organs</td>
<td>15</td>
<td>50*</td>
<td>--**</td>
<td>15</td>
</tr>
</tbody>
</table>

* Changed at 1980 IRPA Meeting to 15.
** Actually given as 5 (N-18); yearly dose not given.
* Actually not given explicitly for this organ irradiated selectively. Dose cited was determined either by using organ weighting factor or using dose for prevention of non-stochastic effects, 50 rems, whichever was less.
** Not given.
# "Other organ" limit interpreted to apply.
## NRC specifies 1.4 rem per quarter, or 3 rem per quarter if specified conditions are met, rather than the 5 given in the table. An annual limit is not stated by NRC although an average annual limit is stated, as 5 (N-18).
Table 2. Summary of reported exposure data to illustrate relative organ doses to personnel in a fluoroscopic facility wearing lead aprons. Refer to original papers for actual interpretation of doses and study methodology

| Study | Eye | Thyroid | Collar | Forehead | Shoulder left/right | Shin, feet, lower legs left/right | Hand left/right | Waist + | Chest + | O+ U+ | O+ U+ |
|-------|-----|---------|--------|----------|-------------------|-------------------------------|----------------|--------|--------|-------|-------|-------|
| St 74 (mrad/ma-min) | -- | -- | -- | 0.8 | -- | 0.01 | 2.6 | 5.1 | 0.05 | 1.2 | 0.1 |
| Ma 72 (mR/exam) | 24 | 34 | 28 | -- | -- | -- | -- | 150 | -- | -- | 530 | 67 |
| Re 78 (mR/exam) | 13.5 | 11.5 | 8.2 | -- | -- | -- | -- | 5.7 | -- | -- | -- | -- |
| Wo 71 (mR/exam) | -- | 28 | -- | 26 | 37 | 10 | 2.0 | 32 | 41 | 22 | 1 | -- | -- |
| Ba 78 (mR/exam) | 7.0 | 8.3 | -- | -- | 6.0 | 5.2 | 40 | 6.5 | 5.7 | 5.8 | 0.4 | -- | -- |
| Be 75 (mR/exam) | 10.7 | 21.4 | -- | -- | -- | -- | -- | 4 | 9 | -- | -- | -- | -- |
| Ch 80 (mR/exam) | -- | 2.8 | -- | 3.1 | -- | -- | -- | 2.6 | -- | -- | -- | -- | -- |

0+ Outside apron
U++ Under apron

or more (Ag78; Ar78; Da81; Ri76; Yo78). Plastic lenses, though, provide negligible protection (Da81; Ri76; Yo78).

Using transmission factors given above, then, for persons wearing leaded eyeglasses or eyeglasses with glass lenses, the reportable overexposures with respect to the lens of the eye would be 33 rem/yr and 10 rem/yr, respectively, for collar monitoring. These corrections that could be applied to personnel monitoring data would become moot if the ICRP recommendations are implemented in the U.S., since the ICRP MPD for the lens of the eye is 15 rem/yr, a value that would rarely be received by anyone in diagnostic radiology. The EPA has proposed, however, that the MPD remain at 5 rem/yr (46 CFR 7836).

(2) Red bone marrow. In the usual case of personnel wearing lead aprons, the majority of the red bone marrow is protected by the apron. The degree of the protection is related to both the lead equivalence of the apron and the half value layer of the beam. From results reported in the literature, a lead apron of 0.5 mm lead equivalent will transmit no more than 20% of a typical diagnostic X-ray beam (Ba78; St74; Wo71; Wo79). The exposed bone marrow outside the apron is contained primarily in the skull, the arms, and the clavicle (in the usual case of the person facing the beam). This amounts to conservatively 25% of the total red bone marrow exposed (Ro76).

Three of the studies in Table 2 (Ba78; Ma72; Wo71) contain data which may be used to estimate the potential bone marrow dose from results obtained at the collar monitoring location. Values for the collar or thyroid may be taken as the exposure at the collar and values outside the apron at the waist or chest may be taken to represent exposure to the vital areas of the bone marrow location without apron, i.e., the long bone of the leg, the ribs, and the sternum. For two of the studies (Ba78; Wo71) for which this comparison could be made, the exposure to both locations reported is similar; for the other, (Ma72) the exposure outside the apron is more than 20 times the collar location and does not appear reasonable again based upon expected patterns of radiation fields. If we thus assume that 75% of the red bone marrow is exposed to approx. 20% of the incident exposure because of attenuation in the apron, then the mean red bone marrow dose would be 25% + (20%)(75%) = 40% of the dose as shown for collar exposures. Thus, for bone marrow irradiation, the reportable exposure level as determined by collar monitoring would be 12.5 rem. This approach is consistent with the previous ICRP position given in ICRP Publication 14 (ICRP69) and is a valid approach to take under existing regulations in making a bone marrow dose assessment.

Current irradiation risk probabilities given in terms of excess cancer incidence due to irra-
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diation of bone marrow may be found in the National Academy of Sciences report, by the Committee on the Biological Effects of Ionizing Radiations (known as the BEIR-III Report) (NAS80). For the linear model, the age and sex weighted estimate of increased leukemia cases per million persons per yr per rad is given as 2.2. In ICRP 26, the risk factor is given as 2.0.

(3) Thyroid gland. Although the thyroid gland has been shown to be relatively sensitive to the oncogenic effects of radiation (NAS80), thyroid cancer is associated with a low mortality rate. The dose limit for the thyroid given by NCRP 39 is 15 rem/yr and in ICRP 26 is 50 rem/yr.* As stated previously, there is no applicable limit for thyroid-only external doses under current U.S. regulations. The BEIR-III report gives a risk estimate of about 4 thyroid carcinomas per 10^6 persons-yr per rad to the thyroid. However, because of the low mortality rate of thyroid cancer, the overall risk factor per rad for health physics purposes for thyroid irradiation is given by ICRP as one fourth that for red bone marrow irradiation.

(4) Other organs. Balter et al. (Ba78), have reported average exposures to the leg below the apron of approx. 5 times the collar exposure, although this may merit further investigation. In terms of current U.S. regulations the pertinent organs would be feet and ankles; these are limited to 75 rem/yr. Thus, it may be seen that a collar exposure indicating 15 rem would have to be received in order that a reportable level would be attained.

Doses to other organs under the lead apron, e.g. the gonads, should be less than 20% of the collar exposure reported because of attenuation by the lead apron.

ICRP DOSE

The ICRP weighted dose equivalent may also be of interest to more realistically view doses to personnel wearing protective devices. ICRP, in ICRP Publication 26, recommends that in the case of partial body exposures individual organ doses should be multiplied by a weighting factor corresponding to the sensitivity of the organ and that the sum of the weighted organ doses be computed. This is expressed mathematically as:

\[ H_w = \sum W_i H_i \]

where \( H_w \) = effective whole body dose equivalent, \( W_i \) = organ weighting factor and \( H_i \) = organ dose equivalent, for each organ or tissue \( t \). These organ weighting factors are given in Table 3.

An example will serve as an illustration of the assumptions and dose computation. From the data in the references cited and given previously in this paper, we will assume that the organ doses, as a fraction of the collar monitor worn outside the lead apron are: (a) gonads—0.2; (b) female breast—0.2; (c) red bone marrow—0.4; (d) lungs—0.2; (e) thyroid—1.0; (f) bone surfaces—1.0; (g) others (taken as dose to GI tract)—0.2; (h) lens of eye—1.0.

In the example assume that the collar monitor indicates a dose of 10 rem. The lens of the eye dose would be less than the 15 rem limit and would not be considered in this computation. The effective whole body dose equivalent for males would be:

\[ H_w = W_{gonads} H_{gonads} + W_{bone\ marrow} H_{bone\ marrow} + W_{lung} H_{lung} + W_{thyroid} H_{thyroid} + W_{bone\ surfaces} H_{bone\ surfaces} + W_{remainder} H_{remainder} \]

\[ = 0.25(10 \times 0.2) + 0.12(10 \times 0.4) + 0.12(10 \times 0.2) + 0.03(10 \times 1) + 0.03(10 \times 1) + 0.3(10 \times 0.2) \]

\[ = 2.42 \text{ rem.} \]

Other \( H_w \) are computed similarly. Actual organ doses using rad/R conversion factors can also be determined which would further reduce the dose assessment. These have been discussed by Wohni and Stranden (Wo79).

*50 rem/yr is given by ICRP as the limit for prevention of non-stochastic effects; actually for stochastic effects (cancer), the use of the ICRP 26 weighting factor implies a dose limit of 170 rem/yr. Thus, the lower limit applies.
Table 3. Specific organ weighting factors ($W_i$) given in ICRP 26

<table>
<thead>
<tr>
<th>Tissue</th>
<th>$W_i$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gonads</td>
<td>0.25</td>
</tr>
<tr>
<td>Breast (Female only)</td>
<td>0.15</td>
</tr>
<tr>
<td>Red Bone Marrow</td>
<td>0.12</td>
</tr>
<tr>
<td>Lung</td>
<td>0.12</td>
</tr>
<tr>
<td>Thyroid</td>
<td>0.03</td>
</tr>
<tr>
<td>Bone Surfaces</td>
<td>0.03</td>
</tr>
<tr>
<td>Remainder</td>
<td>0.30</td>
</tr>
</tbody>
</table>

CONCLUSION

NCRP in Report 57 (NCRP78) states that when doses are well below the MPD, compliance with codes may be demonstrated on the basis of surface dose measured at one point on the body. At levels approaching or exceeding the MPD, the dose to the whole body and the critical organs should be more carefully evaluated and correction factors relating to the circumstances of the exposure should be applied (NCRP78).

This paper has discussed some of the procedures that should be used in evaluating radiation doses to personnel from fluoroscopic X-ray procedures, and the interpretation of these doses using current biological risk factors.

As has been noted, various protective devices may be used in diagnostic radiology. When these are used, notations should be made on the personnel monitoring reports to that effect. Correction factors have been discussed relative to collar exposures which may be applied to the data to account for protection devices and to estimate the "true" dose. These correction factors which may be multiplied by the reported exposure are (a) for the lens of the eye, 1.0, when no glasses are worn; and 0.5 and 0.15 when regular prescription glasses or lead glasses are worn, respectively; and (b) for red bone marrow, 0.4. These appear to be the only critical organs for consideration under present regulations.

The ICRP approach given in ICRP 26 regarding partial body exposures has been applied to the situation of persons wearing protective lead aprons in radiological facilities. The example given has shown that an exposure of 10 R to a single monitor positioned at the collar, outside the apron, indicates an estimated effective whole-body dose equivalent of 2.4 rem. Actual doses to organs are less than estimated doses because of absorption in overlying tissues which is not taken into account in the analysis.

The interpretation of the personnel monitoring data given above should not be construed as implying that exposures that appear unreasonable should not be investigated, even though they may be below the legal limits. Means to reduce exposures to "As Low As Reasonably Achievable" (ALARA) should always be pursued. Additional personnel protective devices for personnel in fluoroscopic X-ray facilities should be used when they are expected to reduce occupational doses.

REFERENCES


BRH78 Suggested State Regulations for Control of Radiation, 1978, Bureau of Radiological Health, HFX-25, FDA, 5600 Fishers Lane, Rockville, MD 20857.


