Operational Topic

Optimal protection by lead aprons against ionizing radiation requires adequate quantitative models for determining their efficacy.

Inspection of Lead Aprons: A Practical Rejection Model

W. Stam and M. Pillay*

Abstract: *As a sequel to the article by Ken Lambert and Tara McKeon, we propose a model by which defects in lead aprons may easily be evaluated on a routine basis. The model is applicable to lead aprons of various lead equivalent thicknesses. As recommended rejection criteria, we have used the concept of additional dose that an individual might receive due to defects in the lead (Pb) apron. The model has been implemented as an annual quality check in a large medical facility. In this article we consider only dose-related rejection criteria, since financial aspects related to ALARA have already been addressed in the abovementioned article. Health Phys. 95(Supplement 2):S133–S136; 2008*

INTRODUCTION

In order to keep the radiation dose received by hospital personnel under normal working conditions as low as reasonably achievable (ALARA), lead aprons and thyroid shields are provided as valuable aids. Intensive use of these accessories could lead to age-related or poor-handling defects often giving rise to multiple tears across the entire apron. Without routine control these lead aprons will, with time, con-

* *Medical Center Haaglanden, Departments of Nuclear Medicine and Radiation Hygiene, Lijnbaan 32, 2512 VA, The Hague, Netherlands.*

Marrimuthoo Pillay is head of Radiation Hygiene and Clinical Physicist Nuclear Medicine at the Medical Center, The Hague. He graduated from the University of London and later completed the Dutch registration in nuclear medicine through the University of Groningen. He is currently liaison officer for the NEA/OECD Nuclear Databank for the Netherlands. His email is m.pillay@mchaaglanden.nl.

tribute significantly to the radiation burden of the wearer.

However, local defects may not necessarily lead to gross changes in the radiation dose received by the wearer. For this reason the location and size of defects are important in evaluating whether a lead apron will need replacing or whether it will require more frequent control. It is recommended to submit lead aprons for inspection at least once a year. In order to quantify any defect detected, we need to know both the size of the defects and their location. In the quantification of a defect we also need to know the lead equivalence of the apron. Finally, the type of lead apron, e.g., single or double layer, is important.

In this article we describe a method by which uniform rejection criteria can be achieved taking the above factors into consideration. We also include criteria for the defects in thyroid lead shielding.

MATERIALS AND METHODS

Additional dose

As a measure of the dose one will receive due to a tear in the Pb apron, we introduce the term "additional dose." The additional dose is defined as the dose that the wearer receives above that which is normally expected for a given transmission and when a tear in the lead apron exceeds a given limiting value. To achieve this limiting value we assume that the additional dose is linearly related to the size of the tear in the apron. The additional dose is, therefore, the dose which will be received above that which will normally be expected if there was no defect.

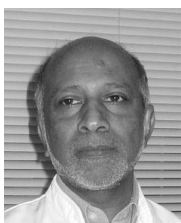The effective dose for a lead apron with a defect with an area a is given by eqn 1:

$$E_{\text{tot}}(a) = w_t \times H \times T \times \left(1 - \frac{a}{A}\right)$$

$$+ w_t \times H \times \left(\frac{a}{A}\right), \quad (1)$$

where w_t = the weight factor for tissue, and $H = H(5)$ the unshielded equivalent dose exposing an effective area A with a transmission T (Lambert and McKeon 2001).
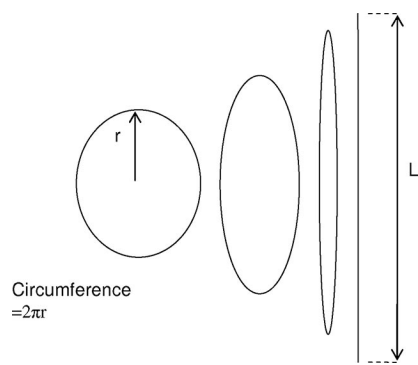
In practice, defects appear as tears with a length L rather then an area a. Therefore, eqn (1) is derived for a tear with a length L (Fig. 1).

To convert from a linear tear of length (L) to area (a), i.e., circle with a maximum area a ($=\pi r^2$) with circumference equal to $2L = 2\pi r$, we get eqn (2) where the radius is substituted for the length:

Figure 1. Conversion from linear tear to area of defect.

$$E_{add}(L) = w_t \times H$$
$$\times \frac{(L^2/\pi)}{A}(1-T). \quad (2)$$

Note that eqn (2) can only be used for protective clothing with a single layer of protective material. For lead aprons which overlap (partially) with double layers of protective material, eqn (3) is derived:

$$E_{add}(L) = w_t \times H$$
$$\times \frac{(L^2/\pi)}{A}(T_s - T_d), \quad (3)$$

where T_s is the transmission of a single layer, and T_d is the transmission of double layers of protective material. Eqn (3) is only to be used on parts with double layers of protective material.

Differentiation in lead equivalence

The transmission of protective clothing is dependent on the incident energy of the photons and the thickness of the protective material. The thickness is expressed in lead equivalences (mmPb), and these values usually apply at a photon energy of around 100 keV.

When the transmission factors of the different lead equivalences are known, it is easy to take these into account. The common lead equivalences for protective clothing are 0.25, 0.35, and 0.50 mmPb. In Table 1 the corresponding transmission factors are given. Note that the transmission for thicknesses

Table 1. Obtained transmission values for aprons of different lead equivalences.

d (mmPb)	Transmissie T (−)
0.25	0.19
0.35	0.10
0.50	0.038
0.70	0.010
1.00	0.0014

0.70 and 1.00 are included where a double layer of protective material is present for 0.35 and 0.50 mmPb. Because of its low contribution, build-up is not taken into account (ICRP 1982a).

Rejection criteria

The rejection criteria are based on the additional effective dose that is applicable on each type of protective clothing and for all lead equivalences. In defining general rejection criteria, it becomes possible to determine, using eqns (2) and (3), the maximum tolerable tear length under the different circumstances.

To establish such rejection criteria we begin with the annual lower limit, e.g., of 2 mSv, i.e., 10% of the annual legal limit of 20 mSv. On the basis of 2 mSv per annum, the maximum tear length will exceed the dimensions of the protective clothing. We therefore introduce the additional dose constraint equivalent to one third of this annual limit producing a more acceptable rejection length. However, this produces rejection tear lengths for double layer Pb aprons of greater than 1 meter, since a small tear can quickly result in a larger defect due to the inherent weight of the Pb apron, decreasing the criteria results to a smaller value for the maximum tear length of the lead apron so that rejection will take place earlier. Empirically a further reduction by a factor 3 establishes realistic and practical rejection criteria (ICRP 1982b).

So finally the rejection criteria are established as indicated in eqn (4):

$$E_{(add.reject)} = 1/3 \times 1/3 \times 2 \text{ mSv}$$
$$= 0.22 \text{ mSv}. \quad (4)$$

Hence, the rejection criteria may be defined as follows: *The rejection is equal to the maximum additional effective dose that is just tolerable, i.e., exceeds a third squared of one-tenth of the annual lower limit—in this case 2 × (1/3)² = 0.22 mSv.*

Definition areas—whole body, gonads and thyroid

From a radiation protection point of view, as well as for psychological reasons, the gonads deserve extra attention (ICRP 2003). It may, therefore, be useful to define an area on the lead apron that is independent of the physical differences between wearers, which has a predetermined location on the lead apron. The applied dimensions for the gonads area amount to 30 × 35 cm² measured 40 cm from the neck-line of the lead apron. The irradiated area is considerably larger than the area of the gonads (22 cm²). Parts of the lead apron outside this area are considered as the "whole body" area.

The differences in tissue weight factor and irradiated organ area, 4,000 cm² for whole body, result in a smaller maximum tear length for the gonads. For thyroid protection an organ area of 22 cm² is applied (Fig. 2).

Correction for exposure geometry—double layers

Lead aprons will primarily be exposed anteriorly. However,
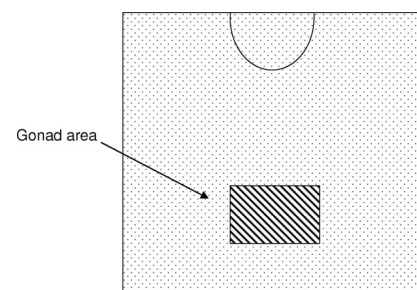
Figure 2. Lead apron showing gonad location.

different activities will mean that lead aprons may also be exposed laterally or posteriorly, depending on the work environment. Double layered lead aprons are constructed such that the overlap takes place in the anterior position so that the anterior aspect will be protected with a double layer of lead. However, the back and on both left and right sides there will be just one layer of protective material, so that eqn (3) is applicable for the front side.

However, the risk of exposure posteriorly or laterally is much smaller than from the front. In the event that the wearer spends a significant amount of time exposed in a posterior or lateral aspect, correction factors have been introduced such that the posterior exposure time was taken as 10% and lateral exposure as 30% of the total time of the anterior exposure.

This means that doses in these directions may be corrected as $10/3\times$ and $10\times$, respectively, in comparison with anterior-posterior (AP) exposure. This results in higher maximum tolerable tear length [factor $\sqrt{(10/3)}$ and $\sqrt{10}$].

Partial doses

To calculate the total additional dose caused by multiple defects, it would be incorrect to sum the lengths and to finally calculate the additional dose. For each defect the additional dose

has to be determined separately and, finally, these partial doses summed as in eqn 5:

$$E_{\text{additional,Total}} = \sum_{tear=i} E_{\text{i}}.$$

(5)

DISCUSSION

Results

In the calculations it is assumed that a lead apron is exposed to an unshielded dose equivalent of 100 mSv (Lambert and McKeon 2001). This is equal to five times the limit for a radiological worker. Because the radiological worker is wearing a lead apron, the unshielded dose equivalent the apron is exposed to is allowed to be five times higher (in case of a 0.25 mmPb apron with $T = 0.2$) resulting in a rejection criterion of 0.22 mSv.

In Table 2 the maximum tolerable tear lengths are shown in relation to the type of protective clothing, the lead equivalence of the material, and the defined area. In addition, the maximum tolerable tear length is given in posterior-anterior (PA) (10%) and lateral (LAT) (30% and 75%) directions for lead aprons that are (partially) provided with a double layer of protective material (0.50 mmPb per layer).

The results for double layered lead aprons show that the maximum tolerable length increases with increasing lead equivalence.

A declaration for this is that $(T_s - T_d)$ (3) approaches zero for higher lead equivalences. The maximum tolerable length decreases with increasing lead equivalence, because $(1 - T)$ (2) ultimately approaches unity.

The results for double layered protective clothing AP direction applied to the whole body vary from 13.5 to 27 cm. These high values can be explained by the fact that there is still another layer of material so that the contribution of a tear is considerably reduced.

However, in practice, it seems that employees who are aware of such defects may have psychological reasons for not wanting to use the lead apron. Besides, the fit and comfort of the protective clothing will suffer under such circumstances, which could influence the overall radiation reduction.

Practical considerations

As a general rule, lead aprons in medical facilities are inspected once a year. We have introduced an additional inspection half-yearly for lead aprons that show marginal defects not yet exceeding our rejection criteria. To demonstrate the rate at which small defects progress, a 10 month follow-up of 8 lead aprons with small defects not exceeding our rejection criteria were found to have an average increase in tears of greater than 270% (from 1.2 cm in 2006 to 3.3 cm in 2007).

In our facility, 96 lead aprons were inspected by the method described of which three (3.1%) were found to have defects producing unacceptable additional doses of 0.62 mSv and 0.79 mSv, respectively. In 2005, when lead apron inspection was first introduced as a standard procedure using previous practices, 12 out of 67 lead aprons were rejected (i.e., 17.9%). We attribute this high rejection rate to the fact that lead aprons were not previously

Table 2. Maximum tolerable tear length (cm) H = 100 mSv.

Type of apron	Definition area	Lead equivalence (mmPb)		
		0.25	0.35	0.50
			AC = 0.22 mSv	
Rejection criterion		Max. length of defect (cm)		
Double AP	Whole body	13.5	17.5	27.0
	Gonads	4.4	5.6	8.7
Single	Whole body	5.9	5.6	5.4
	Gonads	1.9	1.8	1.7
	Thyroid	1.9	1.8	1.8
Double	PA (10%)			17.0
	LAT (30%)			9.8
	LAT (75%)			6.2

inspected and may have had defects long before inspections were introduced.

Figures from another medical facility of equal size to our own and using subjective rejection criteria indicate that they reject about 4.1% (6 out 145) of lead aprons per annum.

Considering these numbers, we can safely argue that the proposed rejection criteria do not lead to excessive rejection, but that the rejected numbers might even become lower as control becomes more enshrined in the quality assurance program.

In our facility, lead aprons have a lifespan of around 8 y. Considering that lead aprons cost around $600, an annual budget of about $1,800-$2,400 could be sufficient for the replacements. Finally, in the process of quality assurance, it is important to pay special attention to the handling and storage of lead aprons. Poor handling and storage could adversely affect the balance between economy and safety.

CONCLUSION

The method described above gives unique rejection criteria that can be applied to different types of radiation protective clothing and different lead equivalences. The obtained rejection criteria are based on an additional effective dose of 0.22 mSv. On this basis it is possible to determine the maximum tear length. Taking into account the radiation sensitivity of the gonads and a separate thyroid shield, three specific areas are defined, namely "whole body," "gonads," and "thyroid." For each of these specific areas, the maximum realistic tear length is obtained.

The obtained results vary from 1.8 cm for the thyroid to 5.9 cm for the whole body for single layered material and from 4.4 cm for the gonads to 27.0 cm for whole body for double layered material.

Furthermore, the possibility is given to make a correction for geometry of exposure. This applies only to double layered clothing. For the AP direction the exposure is set on 100%. For LAT and/or PA the exposure is dependent on the activities. When the exposure is set on 30% and 70% for LAT and 10% for PA, the corresponding maximum lengths are 17.0, 9.8, and 6.2 cm, respectively.

All the obtained values for the maximum tolerable length of defects match with present day rejection practice making the described method a good and practical guide for periodical inspections of radiation protective clothing such as lead aprons.

With this method the ALARA principle is applied in many ways (as seen in the calculations where it is assumed that a defect is exposed as a circle area). In practice, this is the worst case approach. Further, it is assumed that the radiological worker will be exposed to the yearly limit. In good practice, this will seldom occur. Finally, the rejection criteria are based on the lower limit for radiological workers (2 mSv), which results in a smaller maximum tolerable tear. The determined additional effective dose is, therefore, an over-estimation of the actually received additional dose.

REFERENCES

International Commission on Radiological Protection. Protection from ionising radiation from external sources used in medicine. Oxford: Pergamon Press; ICRP Publication 33; Ann ICRP 9(1); 1982a.

International Commission on Radiological Protection. General principles of monitoring for radiation protection of workers. Oxford: Pergamon Press; ICRP Publication 35; Ann ICRP 9(4); 1982b.

International Commission on Radiological Protection. Relative biological effectiveness (RBE), quality factor (Q), and radiation weighting factor (wR). Oxford: Pergamon Press; ICRP Publication 92; Ann ICRP 33(4); 2003.

Lambert K, McKeon T. Inspection of lead aprons: criteria of rejection. Health Phys 80(Suppl 2):S67–S69; 2001.