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Where is a single dosimeter best placed to demonstrate that classification levels are not exceeded during fluoroscopy and ALARP is achieved for unclassified radiation workers? Inside or outside the protective apron: an opinion?

Rosemary A. Nicholson

Under United Kingdom legislation, employers must demonstrate that no unclassified radiation worker exceeds 3/10ths of any dose limit and all doses are as low as reasonably practicable (ALARP). If no substantial radiation dose is envisaged, compliance is conveniently monitored using a single personal dosimeter. Historically this dosimeter has been worn under the protective apron, on grounds that this reflects whole-body dose. Over the years however, radiological practices, protective apron design and dose limits have changed. This study compares the capability of dosimeters both inside and outside the apron to meet legislative requirements. Evaluation entailed reconstructing a typical fluoroscopic layout. Single dosimeters may be attached to a lanyard to hang midline just above waist level. With a front-fastened apron this coincides with an overlapping protective layer and in many procedures the scattered radiation passes obliquely through the double layer. In this study an irradiated Perspex phantom represented the radiation worker and the surface dose was measured above and below one and two layers of 0.35 mm and 0.25 mm lead-equivalence. Incident measurements were up to three orders of magnitude higher than the doses underneath the double layer and thus substantial eye doses can arise before any dose is registered inside the apron. Organs of the trunk adjacent to the overlap can, moreover, receive 20 times the dose beneath the overlap, making ALARP difficult to demonstrate. A dosimeter outside the apron measures no organ dose in itself, but when combined with other data can be used retrospectively to estimate dose to critical organs. It alerts to rising doses and provides an evidence base for issuing multiple dosimeters and for selecting optimal shielding.

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Key words: dose limits, personal dosimetry, ALARP, fluoroscopy, dosimeter position

Introduction

ICRP recommendations & UK legislation

The International Committee on Radiological Protection (ICRP) makes global recommendations on limits to the exposure of radiation workers [1] and these limits are reviewed on a 15 year basis. Back in 1985 the United Kingdom legislated that these limits should be regulated by subdividing radiation workers into classified workers, who are likely to receive more than 3/10ths of any dose limit, and unclassified workers, who are unlikely to reach the 3/10ths level [2].

If a radiation worker is classified, the relevant occupational organ doses must be measured and archived for 50 years in a central database. For workers exposed to lower doses of radiation, a method must be devised to demonstrate they are unlikely to reach 3/10ths of any dose limit in a calendar year. This strategy continued under the Ionising Radiations Regulations enacted in 1999 (IRR99). With current United Kingdom dose limits, an employer must demonstrate that, no unclassified worker can receive more than 6 mSv whole-body dose, 45 mGy to the eye lens and 150 mGy to any 1 cm^2 skin surface in the course of a calendar year (IRR99) [3]. Furthermore, doses must be shown to be as low as is reasonably practicable (ALARP). In hospitals, radiation dose can normally be kept below classification levels for

Formerly of the Radiology Department, St. Mary's Hospital, London, United Kingdom

almost all employees, though the dose limit for the eye is being reviewed with the revision of the Euratom Basic Safety Standards Directive and may be reduced when regulations are rewritten [4, 5].

Position of TLDs

Individual thermo-luminescent dosimeters (TLDs) are commonly used to demonstrate that doses are ALARP and within an unclassified worker's limits, though there may be other equally legitimate methods. Since the cost of TLDs is not insignificant and there is the further expense of local distribution, staff employed in procedures expected to return low dose readings are normally issued with a single dosimeter. Other staff may be issued with additional dosimeters if a significant proportion of any classification dose limit is deemed likely.

Single dosimeters have been worn at waist level in the past, but *kilt-style* aprons make this inappropriate, as the TLD may coincide with *four* layers of protective material and yield no information. However, it is convenient to wear the TLD on a lanyard, along with the mandatory ID card, so it falls midline over the chest, just above waist level.

Study aims

The single dosimeter has traditionally been worn under the protective apron on the basis that this will reflect the dose to radiosensitive organs of the trunk: guidelines reflect this [6]. This study aims to examine the continuing validity of this assumption given current practices and design of protective aprons. It aims to compare dose measurements underneath and outside the protective apron to determine which will most reliably flag up unnecessarily high doses and demonstrate compliance with dose limits.

Methods and materials

It is common for a modern protective apron to have a front fastening, which overlaps to a greater or lesser extent depending on the design of the apron and size of the wearer. This affords extra protection to an operator facing the source of radiation. The lead equivalence of protective aprons is typically 0.35 mm or 0.25 mm. A TLD worn on a lanyard coincides with a double layer of protection for a front-fastened apron and a single layer for other designs. A TLD worn under the apron gives a measure of dose to organs in the vicinity of the TLD. A TLD worn outside the apron gives a measure of environmental dose in the vicinity of the worker.

The arrangement of personnel during a typical interventional fluoroscopic procedure is depicted schematically in Figure 1. The source of most scattered radiation is the volume of the patient being imaged: the operator would be expected to stand at an angle to the incoming scattered radiation, as it is good practice to watch the TV monitor while screening is in progress. This arrangement was reconstructed experimentally using an anthropomorphic Perspex phantom draped in a front-fastened protective apron to represent the radiation worker. A broad beam of X-rays, with energy approximately 7 kV lower than the typical working primary beam energy, was chosen to represent the scattered radiation. Figure 2 shows the fluoroscopic equipment and experimental apparatus.

The source of X-rays was about 1 metre from the surface of the phantom. An ionisation chamber was used as a substitute for the TLD detector, as this returns immediate readings to an accuracy of 0.1 microGy. For procedures involving standard-sized patients, optimal image quality is achieved using primary X-radiation energies in the range 66–80 kV. These X-rays are deflected through an angle of about 90° and/or may be multiply scattered before irradiating the operator. Energy is lost in the process: and therefore this study uses a primary beam of 66 kV X-rays to simulate scatter from standard-sized patients.

A series of measurements was made using 66 kV without added filtration, to represent scatter from a patient screened with a mobile fluoroscopy unit. Another series

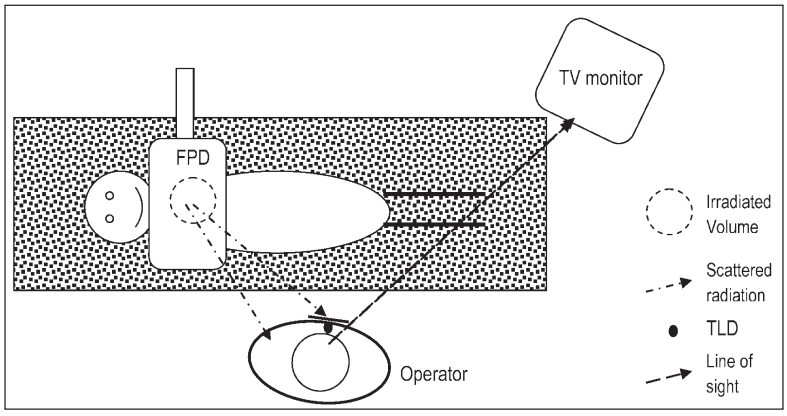

Figure 1. Schematic diagram showing scattered X-ray photons falling obliquely on the overlapping layer of the operator's apron before transmission to the TLD positioned below. Other scattered photons may fall on the single layer at normal incidence. The operator is looking towards the TV monitor while screening

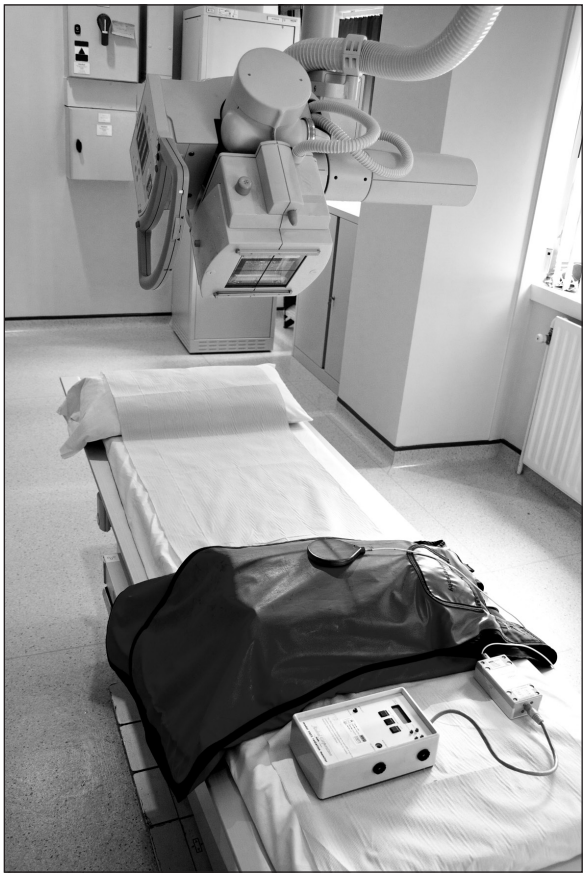

Figure 2. Reconstruction of the shielded 'radiation worker' with X-rays directed on the detector at 45° to normal incidence

was made at 66 kV with 0.2 mmCu and 1 mmAl added filtration, to represent scatter from a patient screened with a fixed fluoroscopy unit. Further measurements were made with a 60 kV primary beam to simulate lower energy scatter such as from orthopaedic procedures, and again with 81 kV and added filtration, to simulate scatter from the screening of large patients (e.g., gastric band procedures) on fixed fluoroscopy units.

Transmission was measured with the radiation at normal incidence to the protective fabric and again at 45° and 60° to normal incidence.

Measurements were made with a Radcal (20 × 5–60) ionisation chamber (Monrovia, California) placed on top of the phantom, first without shielding, then under one and two layers of protection. The process was repeated with lightweight aprons of 0.35 mm and 0.25 mm lead-equivalence and further measurements were made with the chamber resting on the incident side of the apron overlap. The latter is subject to reduced backscatter, so will give a similar reading to the TLD hanging on a lanyard over the double layer. All readings were normalised to the dose at the surface of the phantom with no shielding present.

Further measurements were taken with radiation incident at 45° at the midline, enabling direct comparison of dose under a double layer midline of the worker with the potential maximum dose to organs of the trunk under an adjacent single layer of protection. An overlap of 20 cm was assumed, which was the width of the Velcro fastening incorporated into the apron.

Results

Table I shows how attenuation of the radiation depends on the thickness of the shielding and the angle of incidence. The ratio of transmitted dose at normal incidence through a single layer to the dose transmitted at 45° through the double layer can be 24:1 for the 0.35 mm apron and 16:1 for the 0.25 mm lead-equivalent apron.

This data is consistent with the direct measurements taken when 66 kV X-rays (with or without added filtration) were incident at 45° to the midline of the phantom, on which a protective apron with a 20 cm front overlap had been draped. The ratio of maximum dose (under the single layer) to the midline dose (under the double layer) was 22:1 for the 0.35 mm lead-equivalent apron and 13:1 for the 0.25 mm apron.

The way in which transmission is affected by X-ray energy can be seen in Table II. This data can be used in estimating worst-case organ doses on the few occasions that a substantial dose is unexpectedly registered on a TLD attached to a lanyard outside the apron. For 66 kV X-rays without additional filtration and 66 kV and 81 kV X-rays with 0.2 mmCu and 1 mmAl added filtration, all at normal incidence to a single layer of 0.35 mm lead-equivalent shielding, the ratio of the incident dose measurements (over the apron) to the transmitted dose measurements are seen from Table II to be

Table I. Comparison of transmission of 66 kV X-rays with no added filtration through single and double layers of 0.25 mm and 0.35 mm lead-equivalent shielding for normal incidence and for 45° and 60° angles of incidence. Measurements made using 0.35 mm and 0.25 mm lead-equivalent aprons are displayed in bold and italics respectively

Incident angle of incoming radiation	Dose in front of shielding (reduced backscatter)	Dose at phantom surface without shielding	Dose under 0.25 mm Pb equiv.	Dose under 0.35 mm Pb equiv.	Dose under 0.5 mm Pb equiv.	Dose under 0.7 mm Pb equiv.
0°	81%	100%	4.6%	**1.9%**	0.72%	**0.18%**
45°	83%	100%	2.1%	**0.88%**	0.29%	**0.08%**
60°	87%	100%	1.6%	**0.45%**	0.15%	**0.03%**

Table II. Comparison of transmission of varying X-ray energies at normal incidence through one and two layers of 0.35 mm and 0.25 mm lead equivalent shielding. Measurements made using 0.35 mm and 0.25 mm lead-equivalent aprons are displayed in bold and italics respectively

Incident angle of incoming radiation	Dose in front of shielding (reduced backscatter)	Dose at phantom surface without shielding	Dose under 0.25 mm Pb equiv.	Dose under 0.35 mm Pb equiv.	Dose under 0.5 mm Pb equiv.	Dose under 0.7 mm Pb equiv.
60 kV (no added filtration)	82%	100%	3.0%	**1.1%**	0.35%	**0.06%**
66 kV (no added filtration)	81%	100%	4.5%	**1.8%**	0.72%	**0.18%**
66 kV (with 0.2 mm Cu + +1 mm Al filtration)	74%	100%	10%	**4.9%**	1.8%	**0.53%**
81 kV (with 0.2 mm Cu + +1 mm Al filtration)	72%	100%	18%	**10%**	5.1%	**2.1%**

45:1, 15:1 and 7:1 respectively. For a 0.25 mm lead-equivalent apron the dose ratios are 18:1, 7:1 and 4:1 respectively.

Discussion

TLD accuracy

Using freshly-cleared, state-of-the-art TLDs, doses can be measured to an accuracy of ~5 microSv. If TLDs are to be used as personal dosimeters, however, accuracy is limited by the cosmic and terrestrial background radiation to which they are necessarily exposed for at least a month (Health Protection Agency (HPA) personal communication). TLDs are sensitive to roughly 75 microSv background radiation per month in the United Kingdom. Failure to compensate adequately for this can lead to small, spurious dose readings, which reflect background fluctuations rather than occupational doses, and can be misinterpreted. For this reason, laboratories will not normally attempt to read occupational doses to an accuracy of better than 20 microSv for a month's wear.

Since 2006 high-sensitivity lithium fluoride (LiF) TLDs have been supplied by the HPA for personal dosimetry purposes. LiF is tissue equivalent needing no energy compensation, and there is little fall-off in response for incident angles up to 60°. (This is also true of the RadCal ionisation chamber used in this study as a substitute for a TLD). Underneath the protective apron, however, the dose is dependent on angle of incidence, as radiation passing obliquely through a protective layer travels through an increased amount of shielding. Although the organs beneath the TLD will also receive the lower dose, the reduction in measured dose will not necessarily reflect doses outside the apron or the transmitted dose through other parts of the apron.

Eye doses

Phantom measurements (Table I) show that the limiting measurable dose of 20 microGy per month beneath the double layer of a protective apron may correspond to a dose of 20 mGy or more at an equivalent position with no shielding. The current dose limit to the lens of the eye of a non-classified person is 45 mGy per calendar year, which averages to 3.75 mGy per month. Hence a TLD worn under a front-fastened apron may have insufficient sensitivity to warn of eye doses approaching or exceeding classification level, or rising doses to body parts outside the protective apron.

Although a dosimeter on a lanyard outside the apron may overestimate eye dose by a factor of three or more (depending on the protective measures taken), a worst-case estimate can be achieved retrospectively. These readings will alert to possible increasing eye doses and the need to issue additional dosimeters to reflect eye doses more accurately and demonstrate IRR99 compliance in the future.

Body doses

With the operator standing at an angle to the incoming scattered radiation (Figure 1), a significant part of the trunk may be exposed to radiation passing at normal incidence through a single protective layer, while the measured radiation has been further attenuated by passing obliquely through a double layer. Phantom measurements show that the dose to the trunk under the single layer could exceed the dose measured midline, under a double layer of 0.35 mm lead-equivalent protection, by more than a factor of 20. Again, the average dose to organs of the trunk could become significant before the TLD responds.

A dosimeter outside the apron is exposed to higher intrinsic doses. Dose constraints can be set for these readings, and should a significant environmental dose be identified, a worst-case, whole-body dose can be estimated retrospectively, especially if the apron type is known. Additional dosimeters can then be issued, as required, for the future.

Skin doses

Skin dose limits are a factor of 25 higher than whole-body dose limits. *Operator hand* doses were assessed using

an ionisation chamber while the anthropomorphic phantom (now representing the patient) was being screened. Results showed that the hand of the operator, if positioned comfortably, outside the primary beam and with the tube predominantly under the table is unlikely to receive more than 4 times the dose recorded on the lanyard.

Similarly, although the *shins of operators* will normally be shielded by table-mounted screens, comparison of environmental TLDs attached routinely at knee height and chest height to the C-arm of our mobile fluoroscopy units demonstrated that shin doses are unlikely to exceed environmental dose at chest level by more than a factor of 6, even without additional shielding.

If an X-ray dose on the TLD worn outside the apron is less than the whole-body classification level, *extremity doses* can reasonably be expected to also lie below the extremity classification level.

Nuclear medicine

Nuclear medicine is, of course, a different category from X-ray fluoroscopy, and the technologist's *forefinger dose* will normally be measured routinely.

The practical situation

On adopting high-sensitivity TLDs it was noticed that many highly significant eye dose measurements were *not* associated with a measurable dose beneath the apron. For this reason, the hospital staff who had been issued with single dosimeters were asked to wear these dosimeters on lanyards outside their protective aprons. These workers would probably have been wearing a variety of apron styles; some would have used ceiling-mounted shields on occasions; and others might have rotated through nuclear medicine and worn no protective apron for part of the time.

Certain staff, who regularly carried out interventional procedures continued to be supplied with two or more whole-body style dosimeters, one worn at thyroid level, to reflect eye dose, and one under the protective apron, preferably beneath the single layer and on the side closest to the source of radiation. Staff with a high interventional workload were routinely offered finger dosimeters, as were nuclear medicine staff.

It is difficult to guarantee that dosimeters are correctly worn at all times, but the Radiation Protection Supervisors (RPSs), on the whole, are vigilant and spot checks are practicable. Few of the 300+ whole-body dosimeters in the two-monthly issues registered doses significantly above background and very rarely did monitoring outside the apron return a total annual dose above the whole-body limit for unclassified workers. Where this occurred, higher doses had been anticipated and personnel supplied with second dosimeters, which normally registered a negligible dose under the apron. There was a single occasion when a high pro-rata dose was incurred. A registrar, new to the hospital and working in interventional radiology, returned a dose of 8.5 mGy on a single dosimeter worn on a lanyard outside 0.35 mm lead-equivalent aprons for two months. He felt confident that his working practices were similar to those of the previous three years when he had worked at other hospitals, but earlier dosimeters, worn as instructed under the apron, had not alerted him to any measurable dose. We could say retrospectively that no part of the body under the 0.35 mm lead-equivalent apron was likely to have received more than 10% of the recorded dose, but he was subsequently issued with additional dosimeters and closely monitored for his remaining time with our hospital.

Whatever the mode of working, it can reasonably be concluded that the environmental dose measured on a lanyard outside the protective apron will never exceed the true whole-body dose and if the worker knows what protection she/he has been using, a more accurate retrospective estimate of whole-body dose can be made. If the worker chooses a 0.35 mm apron, the whole-body dose is unlikely to be higher than 15% of the measured dose and probably less than 7% of this dose for any apron design (see Tables I–II). If a 0.25 mm lead-equivalent apron is used the whole body dose is unlikely to exceed a quarter the measured dose and is likely to be less than 10% of this dose. (The higher penetrations would only occur if unusually high X-ray energies had been persistently generated).

If any environmental dose reading approaches the pro-rata whole-body classification level, or if doses approaching half this value are repeatedly returned, multiple dosimeters may be considered necessary to demonstrate compliance with IRR99, though these numbers are likely to be relatively small. The use of TLDs to estimate eye and skin doses has been discussed in detail by Martin [7]. If the environmental dose recorded by a TLD on a lanyard is below whole-body classification level, however, compliance with all classification limits can normally be assumed. Exceptions may be the foetus in pregnancy and nuclear medicine finger doses.

TLDs were worn on a two-monthly basis, with few exceptions where it was deemed necessary to issue two dosimeters, the first being processed after the first month. A two-month wear period was chosen primarily to simplify logistics and ease the workload of those distributing and collecting the dosimeters. It also reduced the cost of supply.

Low-dose measurements can benefit from an extended wear period, with an improved signal-to-noise ratio. Allowing for a one-month changeover period (to include the time from erasure to wearing and from wearing to reading), the two monthly issue gives a longer sampling period and is balanced against three months' exposure to background radiation. This is compared with one month's wear and two months' exposure to background. The downside is that problems could take three months to identify, compared

with two months for the monthly issue: although in practice this has never been a real difficulty.

Environmental radiation exposure can change rapidly with distance and irradiated volume (among other factors), thus a wide variation in the exposure of radiation workers is to be expected. Monitoring outside the apron may show that the vast majority of radiation workers are exposed to very low levels of radiation; and this in turn raises the question of whether they need to be monitored at all.

Environmental dosimeters strategically attached to equipment such as the C-arms of mobile fluoroscopy units can be used to demonstrate that many staff are well below classification levels. This technique avoids the problem of irregular wear through human oversight. Such monitoring, however, is not always appropriate, especially with the high workloads of fixed fluoroscopic equipment as it can only return the total dose received by a number of staff. Most staff are reassured by the offer of monitoring, and it is not onerous to wear a dosimeter with the mandatory ID card on a lanyard.

In the pre-TLD era the technology of film-badge dosimetry (using small pieces of silver bromide film) required processing to take place on a monthly basis to deliver the necessary accuracy. With TLDs, however, the option is open to extend the wear periods, if appropriate, for up to three months. Readings, though frequently negligible, will confirm that doses are as low as is reasonably practicable and can form an evidence base on which to triage workers, so multiple dosimeters can be provided as required and the most suitable weight and design of apron can be identified.

Whether the dosimeter is worn under or over the apron, the role of the RPS is crucial to proper control of radiation safety. The argument can be made that a dosimeter worn under the apron has the advantage of flagging up an employee declining to wear a protective apron in accordance with local rules: provided the same employee is diligent about wearing the dosimeter. Similarly, readings from a TLD under the apron may alert to a weakness in the apron: provided the flaw coincides with the position of the TLD and provided the flawed apron is repeatedly chosen by the same individual. For single dosimeters worn under the apron, the short-term issue of a second dosimeter (outside the apron) is recommended if any high doses could be anticipated. If the dosimeter is worn outside the apron the need for the second dosimeter is immediate and evidence based, taking out guesswork.

Single dosimeters, correctly worn outside the apron, can be used to demonstrate compliance with all dose limits. If ALARP is to be assured, however, the RPS should further be vigilant in ensuring that aprons are intact and are being worn as required by local radiation protection rules, especially if low but repeated readings are being returned.

Zero dose measured under a double-protective layer confirms that doses to organs in the locality of the dosimeter are negligible, but the equivalent zero measurement taken outside the apron is of much more significance. Measures taken to reduce radiation risk can have the downside of discomfort, and arguably increase the risk of injury to the back. These related risks can be minimised if personal dosimetry data provides evidence upon which to optimise the selection of aprons offered to X-ray workers and upon which the individual worker chooses their optimum weight of apron. (The latter is an individual decision and can be influenced by circumstances such as possible pregnancy). Low and negligible doses outside the apron are likely to be common. They do not necessarily constitute valueless information, but can provide important reassurance that no high doses have been incurred and all doses have been as low as reasonably practicable, should circumstances change and questions arise in the future.

Rosemary A. Nicholson, MSc
Flat 2, 40 Durand Gardens
London SW9 0PP
United Kingdom
e-mail: ranicholson@waitrose.com

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