Guidance on the use of protective lead aprons in medical radiology
Protection efficiency and correction factors for personal dosimetry

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Summary
Workers in clinical radiology wear lead aprons when standing in the vicinity of a patient being exposed to x-rays. A lead apron protects the person's trunk against radiation scattered from the patient. Our research focused on two main issues:

1. How much protection does a lead apron provide, and what are the main factors that determine the protection efficiency
2. How can measured badge dose be translated into a realistic estimate of the effective dose, and how does this depend on dosemeter placement

Using a model for x-ray shielding and dosimetry we calculated equivalent organ doses and personal depth dose Hp(10) for various exposure conditions, x-ray energies and types of aprons that occur in clinical practice.

We concluded that apron model and fit are often more important than lead thickness. In others words, increasing lead thickness of a badly chosen apron will not provide better protection. For many fluoroscopy applications an apron of good model and fit need not be thicker than 0.25 mm of lead (equivalent). In case of intensive and frequent interventional work lead we advise higher lead thickness (0.35 mm), and preferably additional neck shielding for protection of the oesophagus and thyroid. A well chosen lead apron reduces effective dose by 75% up to 90%.

We also concluded that the dosemeter badge should always be worn outside the apron, at "mid front" of collar or chest. In our view this dosemeter position enables reliable evaluation of effective dose from badge readings. As a standard practice we recommend translating measured badge dose to effective dose by dividing by a factor of five (5), provided that the worker wears a suitable lead apron.

Finally, some research was done on the subject of the protective effect of lead aprons for the uterus, and the relation of uterus dose and badge dose. Use of a lead apron is found to reduce uterus dose by a factor of 5 to 10. Our study shows that in case of worker pregnancy, exposure of the unborn child may be adequately monitored by a specifically designated dosemeter worn locally under the lead apron.

Introduction

Effective dose cannot be measured in a direct way. It is not a measurable dosimetric quantity, but rather an arithmetic concept that enables one to compare the implications of very different exposure situations. In short, effective dose is the weighted sum of equivalent doses per organ, using the weighting factors recommended by ICRP publication 60.

For many exposure situations a good estimate of effective dose can be made using specifically calibrated instruments, like, for instance, personal TLD dosemeters. Most dosemeters for personal use are calibrated under the assumption that a person is uniformly exposed to a broad parallel beam from the front to the back (AP). The dosemeter should then be worn on the front of the body. Technically speaking, the conversion coefficient from the operational quantity 'personal dose equivalent' to effective dose is close to unity.
If exposure conditions are not that simple, this conversion coefficient may greatly deviate from unity. Assessment of effective dose should then be done using (model) calculations that adequately represent the actual exposure conditions.

Model calculations

In case of exposure to low energy scattered x-rays, determining equivalent doses is quite complicated due to radiation attenuation in body tissues. Depth dose distribution is highly dependent on radiation energy and exposure geometry. Use of protective lead aprons adds a lot of complexity because of complete or partial shielding of organs.
We developed a model that calculates equivalent doses in function of scattered x-ray spectrum [Feh96], shielding parameters and exposure geometry. The model assumes broad parallel beams, simulating orientation and movement of a person in a radiation field by a combination of exposure geometries: Anterior-Posterior (from the front), LATeral (from the side) and Posterior-Anterior (from behind). Equivalent organ doses are calculated per unit entrance kerma in air, at the surface of the trunk, using the appropriate conversion coefficients obtained from Monte Carlo studies in

mathematical phantoms [ICR98]. For each exposure scenario we calculated effective dose according to ICRP-60 definitions [ICR91].

We performed model calculations for a wide variety of practical situations, with and without a lead apron, and for many apron models, fits and lead thickness. For each specific case we determined effective dose reduction, in function of x-ray tube voltage and exposure geometry. The effective dose reduction is a measure of the protective effect.

In addition to calculation of equivalent dose, the model also determines personal dose equivalent, or shortly 'badge dose' [ICR87]. This calculation refers to dose equivalent at a depth of 10 mm in tissue, on the front of the body, outside a protective apron ($HP_{unshielded}$) or under the apron ($HP_{shielded}$). For each exposure scenario we determined the ratio of calculated badge dose and the corresponding value of effective dose. These ratios enable us to translate personal dosimetry results to a better estimate of the actual effective dose.

All results of the model calculations are available from the author in the form of a database.

Protection efficiency

The protective effect of a lead apron can be characterised by the concept of 'protection efficiency'. It is a number that indicates the percentage of dose reduction that is obtained by wearing a specific lead apron. Protection efficiency varies with lead thickness, x-ray tube voltage and exposure geometry. Yet, for aprons thicker than 0.25 lead, efficiency is largely determined by apron fit, because fully or partially unshielded organs contribute most to effective dose. Figure 1 summarizes our results for typical clinical x-ray intervention conditions: that is the use of so called 'wrap around' aprons without additional thyroid shield, in a mixed exposure situation (geometries: 60% AP, 30% LAT and 10% PA). These results turn out to be valid also for frontal aprons in a predominantly frontal exposure geometry, with 20% lateral contribution.

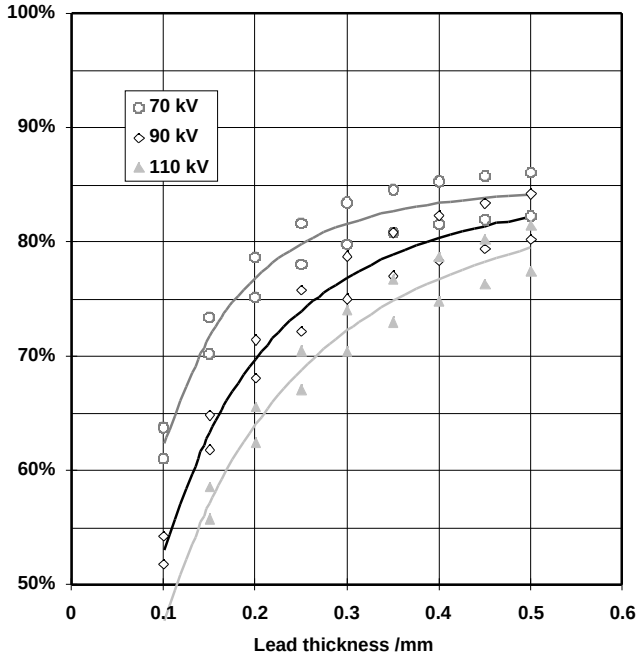

Figure 1: Protection efficiency of lead aprons without thyroid protection shield. Lines indicate mean values, markers illustrate variation due to apron fit.

We derived a rule of thumb that provides a good estimate of protection efficiency of an apron for known values of x-ray tube voltage (kV) and lead thickness (Pb, mm):

$$protection\ efficiency \approx 85 - \frac{kV - 50}{20 \times Pb}$$

This formula is valid for aprons of reasonably good fit, without additional thyroid protection. One must be careful in case of so called 'light weight' aprons. This type of protective aprons is usually made of composite material, containing both lead and some other elements like tungsten, barium etc. Specified lead equivalence can only be valid for a range of x-ray tube voltages. The supplier of such aprons should specify this range.

Our calculations show that 0.25 mm frontal aprons of good fit provide at least 70% protection, which is adequate for general radiology purposes. For interventional radiology, involving lateral and dorsal exposure, 0.35 mm wrap around aprons are recommended in order to achieve the same level of protection. Thicker aprons do not provide much more protection, but they do add a lot of weight. Use of an additional thyroid (neck) protector reduces effective dose by another 5 to 10%, due to shielding of the thyroid and oesophagus. A combination of a 0.35 mm lead apron and 0.25 mm thyroid shield yields the optimal protection efficiency (85% to 90%).

Correction factors for the interpretation of personal dosemeter readings
A single badge dosemeter worn outside the lead apron will generally overestimate effective dose. Effective dose can be assessed by dividing the unshielded badge reading by a correction factor. Appropriate correction factors were dtermined by model calculations.
The calculated correction factors for translating unshielded badge dose reading to the actual personal dose (effective dose) are shown in Figure 2, for wrap around aprons in a mixed 60% AP, 30% LATeral en 10% PA exposure geometry. In order to avoid underestimation of effective dose, we assumed that only AP exposure contributes to badge dose. In actual circumstances the personal dosemeter reading may be somewhat higher, resulting in a higher evaluated value of effective dose.

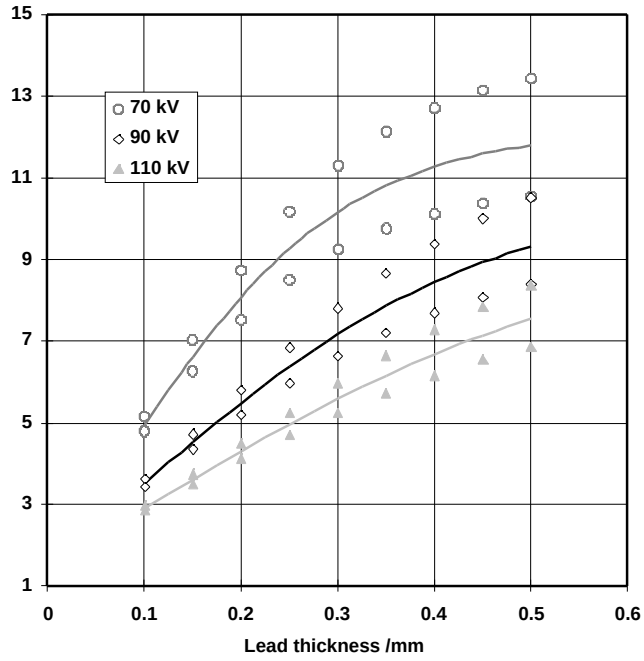

Figure 2: Correction factor for unshielded badge depth dose. Lines indicate mean values, markers illustrate variation due to apron fit.

We conclude that a division factor of 5 yields a conservative estimate of effective dose, in case of a single badge personal dosemeter worn outside the apron, mid front at collar or chest level.

$$effective\ dose \leq \frac{1}{5} \times HP_{unshielded}$$

It is a well known fact that working practices exist, where annual effective doses of workers amount to a substantial fraction of the occupational dose limit (for instance cardiac and vascular x-ray intervention). In such conditions a dual badge dosimetry protocol should be considered [ICR82]. One dosemeter is worn outside the apron (mid front at collar level) and the other is worn under the apron (mid front at waist level). Combining the two dose readings will deliver a more accurate assessment of effective dose.
We derived a simple formula to do this. It is constructed in such a way that effective dose is estimated as accurately as possible, but never underestimated:

$$effective\ dose \le \frac{1}{10} \times HP_{unshielded} + HP_{shielded}$$

The formula may overestimate effective dose by up to 50%, in exposure conditions that occur in interventional radiology. It is valid for aprons of at least 0.25 mm lead thickness, without thyroid protection, provided that the apron model and fit suit exposure conditions. If a thyroid shield is used, the following formula should be used instead:

$$effective\ dose \le \frac{1}{30} \times HP_{unshielded} + HP_{shielded}$$

We advise against a dosimetry protocol using a single badge under the apron. Our study demonstrated that often effective dose cannot be adequately reconstructed, because the actual detection limit is greatly increased by the apron's shielding effect. This is especially true for low x-ray tube voltages (below 100 kV), but even at higher tube voltages detection limit is increased by a factor of 10 to 20. Another argument against such a protocol is the fact that a shielded badge reading can never be used to assess unshielded tissue exposure, such as the eye lens.

Uterus dose

For (possibly) pregnant female workers, dose control of the abdominal region is of special interest in radiation protection. We use the uterus dose equivalent as a first approximation of the dose to the foetus. The protection factor for the uterus is defined as the ratio of uterus dose without and with shielding respectively. Values for the protection factor for the uterus are given Fig.3, in function of lead thickness and tube voltage. This shows that both frontal aprons in a predominantly AP orientation and wrap-around aprons in a mixed geometry guarantee a protection factor above 5, even for very high tube voltages, if lead thickness is 0.25 mm.

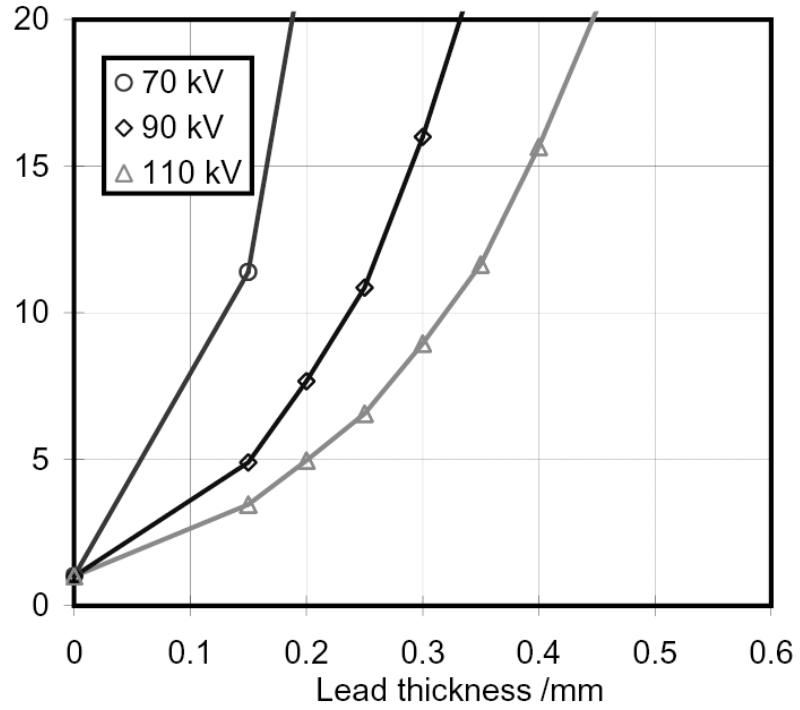

Figure 3: Protection factor for uterus

In case of (possible) pregnancy a special dosemeter may be worn at the surface of the abdomen under the apron, for dose control for the unborn child. We analysed the relationship between such depth dose measurements and the uterus dose. Our data demonstrate that the uterus dose is always slightly overestimated (Fig.4). In view of the uncertainties that are associated with operational dosimetry, a prudent first approach is to use the uncorrected shielded depth dose to estimate the equivalent dose to the uterus. If, for special reasons, a more precise estimate is wanted, one may divide the reading by the appropriate correction factor from Fig.4.

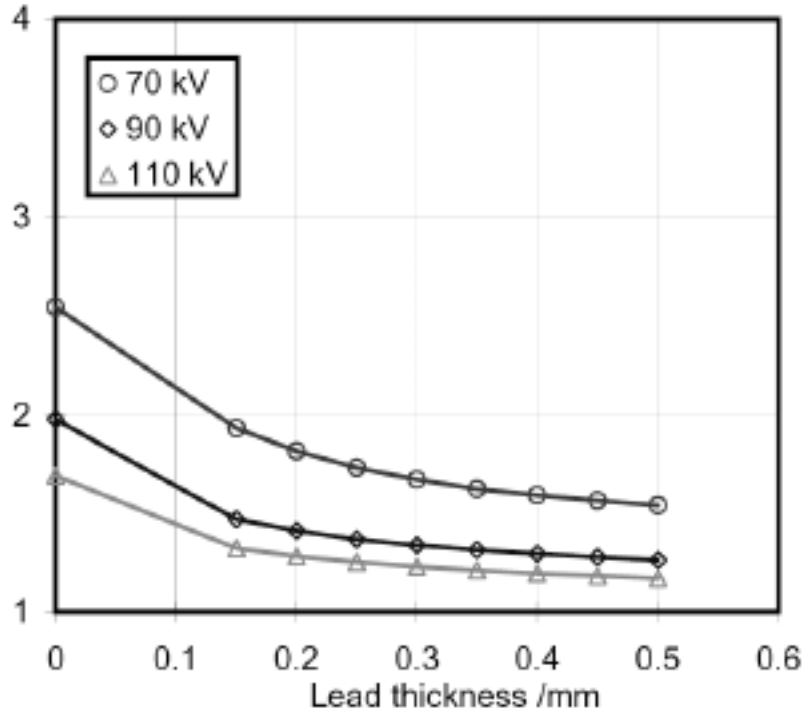

Figure 4: Overestimation of equivalent dose to the uterus by shielded depth dose measurements

References

[Feh96] G. Fehrenbacher, W. Panzer en K. Tesfu. Spectra of diagnostic X-rays scattered by a water phantom. GSF-Forschungszentrum für Umwelt und Gesundheit, Institut für Strahlenschutz. GSF-Bericht 9/96.

[ICR98] International Commission on Radiation Units and Measurements. Conversion coefficients for use in radiological protection against external radiation. ICRU Publication 57 (Bethesda, Ma, USA)

[ICR91] Recommendations of the International Commission on Radiological Protection. ICRP Publication 60 (Oxford; Pergamon)

[ICR87] Recommendations of the International Commission on Radiological Protection. ICRP Publication 51 (Oxford; Pergamon)

[ICR82] Recommendations of the International Commission on Radiological Protection. ICRP Publication 35 (Oxford; Pergamon)

[Huy95a] Chr.J. Huyskens en Y. Franken. Assessment of effective dose for medical x-ray workers. Proceedings International conference on Radiation Protection and Medicine, Montpellier, France, 28-30 June 1995

[Huy95b] Chr.J. Huyskens. Protective effect of lead aprons in medical radiology. Strahlenschutz Praxis, 1, 4, 43-47 (1995)

[Huy96] Chr.J. Huyskens, Y. Franken. Assessment of effective dose and uterus dose for workers in medical radiology. Proceedings IRPA international congress on radiation protection, Vienna, Austria, 14-19 April 1996