X-Ray Protective Aprons Re-Evaluated

Röntgenschürzen – neu bewertet

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ABSTRACT

Background The evaluation of the protective effect of X-ray protective clothing requires new criteria. The current concept assumes more or less uniform covering of the torso with protective material. The frequently worn heavy wrap-around aprons can weigh 7 to 8 kg. As relevant studies show, orthopedic damage can result from long-term activity. It should therefore be investigated whether the apron weight can be reduced by optimizing the material distribution. For a radiobiological evaluation of the protective effect, the “effective dose” should be used.

Methods Numerous laboratory measurements were performed with an Alderson Rando phantom as well as dose measurements on clinical personnel. The measurements were supplemented by Monte Carlo simulation of an interventional workplace in which a female ICRP reference phantom was used for the operator. The measured back doses on the Alderson phantom as well as the measured back doses at interventional workplaces were based on the personal equivalent dose Hp(10). Monte Carlo simulations were used to introduce protection factors for the protective clothing based on the “effective dose” introduced in radiation protection.

Results Back doses in clinical radiology personnel are largely negligible. Therefore, back protection can be much lower than currently used or can even be eliminated. The Monte Carlo simulations show that the protective effect of protective aprons worn on the body is higher than when the flat protective material is radiated through (3 D effect). About 80 % of the effective dose is attributed to the body region from the gonads to the chest. By additional shielding of this area, the effective dose can be lowered or, optionally, aprons with less weight can be produced. Attention must also be paid to the “radiation leaks” (upper arms, neck, skull), which can reduce the whole-body protective effect.

Conclusion In the future, the evaluation of the protective effect of X-ray protective clothing should be based on the effective dose. For this purpose, effective dose-based protection factors could be introduced, while the lead equivalent should be used for measurement purposes only. If the results are implemented, protective aprons with approx. 40 % less weight can be produced with a comparable protective effect.

Key Points:
- The protective effect of X-ray protective clothing should be described by protection factors based on effective dose.
- The lead equivalent should only be used for measurement purposes.
- More than 80 % of the effective dose is attributed to the body region from the gonads to the chest.
- A reinforcing layer in this area increases the protective effect considerably.
- With optimized material distribution, protective aprons could be up to 40 % lighter.

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ZUSAMMENFASSUNG

Hintergrund Die Bewertung der Schutzwirkung von Röntgenschutzkleidung bedarf neuer Kriterien. Das jetzige Konzept geht von einer mehr oder weniger uniformen Abdeckung des Rumpfes mit Schutzmaterial aus. Die häufig getragenen schweren Rundumschürzen können es durchaus auf 7 bis 8 kg bringen. Wie einschlägige Studien zeigen, können bei langzeitlicher Tätigkeit orthopädische Schäden die Folge sein. Es ist daher zu hinterfragen, ob das Schürzengewicht nicht durch eine Optimierung der Materialverteilung reduziert werden kann. Für eine strahlenbiologische Bewertung der Schutzwirkung wird dabei auf die effektive Dosis zurückgegriffen.

Methoden Es wurden zahlreiche Labormessungen mit einem Alderson-Rando-Phantom sowie Dosismessungen an klinischem Personal durchgeführt. Ergänzt wurden die Messungen durch die Monte-Carlo-Simulation eines interventionellen Arbeitsplatzes, bei dem für die Untersucherin ein weibliches ICRP-Referenzphantom verwendet wurde. Die Messungen am Phantom wie auch die Messungen der Rückendosen an interventionellen Arbeitsplätzen stützten sich auf die Messgröße Personen-Äquivalentdosis Hp(10). Mithilfe von Monte-Carlo-Simulationen wurden Schutzfaktoren für die Schutzkleidung eingeführt, die auf der im Strahlenschutz eingeführten „effektiven Dosis“ basieren.

Ergebnisse Die Rückendosen bei klinisch-radiologisch tätigem Personal sind weitgehend vernachlässigbar. Der Rückenschutz kann daher wesentlich geringer ausfallen als derzeit üblich oder sogar entfallen. Die Monte-Carlo-Simulationen zeigen, dass die Schutzwirkung von Schutzschürzen, die am Körper getragen werden, höher ist als bei Durchstrahlung des flachen Schutzmaterials (3D-Effekt). Rund 80 % der effektiven Dosis entstehen von den Gonaden bis zur Brust. Durch eine zusätzliche Abschirmung dieses Bereiches kann die effektive Dosis gesenkt oder wahlweise Schürzen mit weniger Gewicht hergestellt werden. Das Augenmerk muss auch auf die „Strahlenlecks“ (Oberarme, Hals, Schädel) gerichtet werden, die die Schutzwirkung für den Gesamtkörper herabsetzen können.

Schlussfolgerungen Die Bewertung der Schutzwirkung von Röntgenschutzkleidung sollte künftig auf der Basis der effektiven Dosis erfolgen. Dazu könnten Effektivdosis-basierte Schutzfaktoren eingeführt werden, während der Bleigleichwert ausschließlich Messzwecken dienen sollte. Bei Umsetzung der Ergebnisse lassen sich bei vergleichbarer Schutzwirkung Schutzschürzen mit ca. 40 % weniger Gewicht herstellen.

Background

Protective effect and weight are important parameters in the evaluation of X-ray protective clothing. However, these two elements are antagonists, i. e., higher protection and lower weight seem incompatible. Studies show that a high percentage of radiology personnel complain about orthopedic problems in part because of heavy protective clothing [1–4]. The frequently worn wrap-around aprons can weight 7 to 8 kg. In the case of long-term activity, orthopedic damage can occur due to the additional weight on the joints and spine. Therefore, the EU regulations for market approval of X-ray protective equipment [5] state that such equipment must be as light as possible.

This issue seemed to be resolved or minimized by the introduction of lead-free protective aprons with an estimated weight reduction of 30 %. However, detailed laboratory tests and the introduction of a new measurement procedure determining the fluorescence radiation and scatter radiation of the material showed that the initial enthusiasm was unfortunately not justified [6–9]. With respect to achieving the same protective effect at the lower apron weight, the lead-free aprons often can only be used in a limited kV range.

A new possibility for lowering the weight while maintaining the same protective effect is to optimize the distribution of the protective material on the body. The effective dose should be used as a target parameter which is included in radiation protection as a protection parameter [10, 11].

During interventional procedures and angiography examinations, the patient is usually in a lying position. The irradiated patient volume emits scatter radiation with a broad directional distribution so that the protective layer of the apron is primarily not radiated through in a perpendicular manner but rather at an angle. Therefore, the specified lead equivalent, which is calculated using a perpendicular irradiation scenario, does not reflect the real patient/examiner scenario. The lead equivalent is simply a value of the materials used and indicates at best the indirect protective effect of the apron as a three-dimensional structure.

The goal of previous studies was to develop methods for practice-based evaluation of the protective effect of protective aprons on the basis of effective dose and to provide criteria for efficient distribution of the protective material on the body. These studies were based on the clinical patient scenario in interventions, cardiology examinations, and angiography examinations using patient-equivalent scatter radiation.

Definitions

The effective dose without a protective apron divided by the effective dose with a protective apron is referred to as the effective dose-based protection factor F_{Teff}. The protection factor relates to the torso and not the whole body in the following.

The protection factor related to the whole body including the skull and extremities is referred to as the whole-body effective dose-based protection factor F_{Geff}.

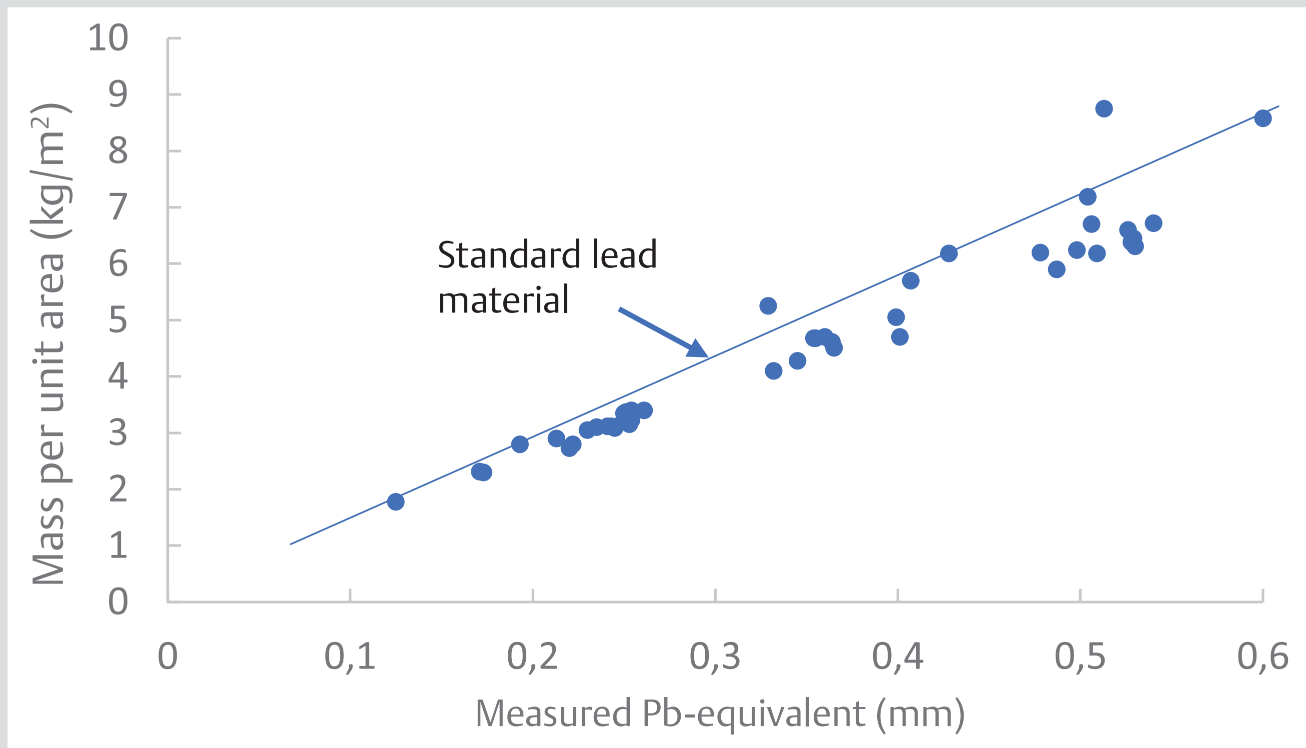
Protection factors can be defined in the same way for individual organs as F_{Org}.

The *dose area product* is calculated as air*surface (gray*square centimeters, *Gy*cm²*).

The equivalent dose at a tissue depth of 10 mm at the site of the dosimeter is referred to as the personal dose equivalent $H_p(10)$.

The *effective dose E* (unit: sievert) is the sum of the equivalent doses weighted based on risk in the individual organs of the body.

Attenuation factors $F_{Pb\ equivalent}$ are used for the *lead equivalent* on which the current apron standards are based. These are calculated by the air kerma without protective material divided by the air kerma with protective material in the case of radiation at right angles.

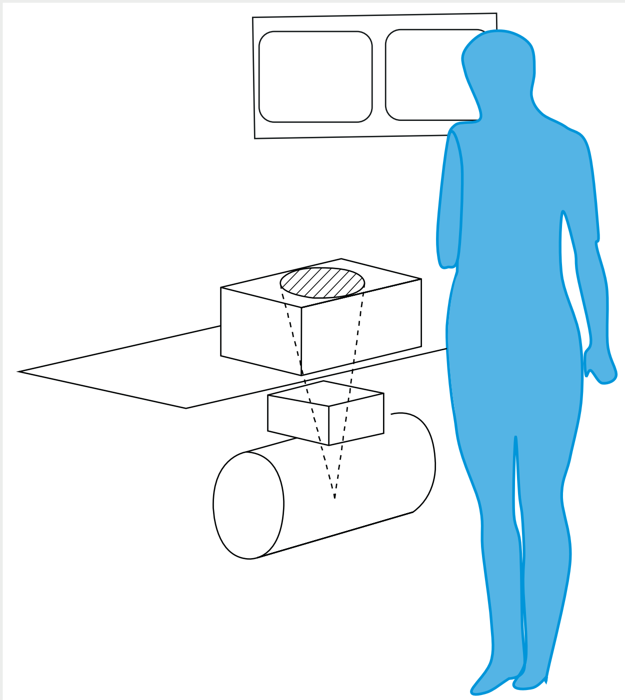


▶ **Fig. 1** Results of lead equivalent measurements and weight measurements for commercially available protective materials. Lead aprons are located near the line. Lead-free aprons and lead-reduced aprons are located under the line. The maximum weight reduction compared to lead aprons is approximately 17 %.

Studies to date

This article provides a short overview of the studies to date (our own and others). Further details can be found in the original documents.

1. Determination of lead equivalents vs. mass per unit area of protective clothing as part of certification according to the European Guidelines for Personal Protection Equipment, reference: measurements of the author during certification (▶ **Fig. 1**).
2. Ref. [10, 11] Laboratory measurements of the personal dose equivalent with four $H_p(10)$ dosimeters distributed on the front side of a male Alderson phantom to estimate the effective dose. A water phantom served as the scattering body. Configuration corresponding to the clinical conditions during interventions. Various orientations of the phantom with tube voltages 80, 100, 120 kV and various lead equivalents of the protective clothing were used. Type-tested, calibrated $H_p(10)$ dosimeters ("Trudose") were used for the measurement of the personal dose equivalent.
3. Ref. [10, 11] Monte-Carlo simulations for a clinically realistic patient-examiner scenario with determination of the effective dose-based protection factors for the protective apron.
4. To determine the breast dose, a female ICRP 110 reference model [12] was placed as the examiner in various positions with respect to a patient phantom (water phantom according to DIN 6815). The fundamental patient/examiner setup is shown in ▶ **Fig. 2**. Approximately 20 simulations with various orientations of the examiner with respect to the patient in lying as well as standing positions were performed. The tube voltages were 80/100/120 kV. Protective clothing with lead equivalents of 0.25/0.35/0.50 mm was used.
5. Ref. [13] Monte-Carlo calculations for determining the effective dose based on a monochromatic parallel X-ray beam and an ICRP 110 reference model wearing a protective apron with a lead equivalent of 0.5 mm. The effective dose-based protection factors were calculated by dividing the effective dose without a protective apron by the effective dose with a protective apron. The radiation was modeled as a parallel field with discrete energy levels of 20 to 120 keV with various angles of incidence in relation to transverse and sagittal planes of the person to be protected. The whole body including unprotected body parts was exposed.
6. Ref. [14] Measurement of the back dose under laboratory conditions using the Alderson phantom as well as when working at interventional workstations and CT scanners. The calibrated $H_p(10)$ dosimeters were applied in the center of the back on top of the protective clothing. The measurements were performed for randomly selected examinations and interventions.
7. Ref. [15] The starting point here was orthopedic damage among persons performing interventions. The weight and protective properties of various commercially available aprons with lead equivalents of 0.25/0.35/0.50 mm were examined. $H_p(10)$ *dosimeters* were worn over and under the apron and the attenuation was calculated.



▶ **Fig. 2** Typical configuration of patient phantom/female reference phantom for a patient in a lying position and a PA X-ray beam, here: 30° rotation of the examiner looking in the direction of the monitor.

Summary of the results

Lead equivalent vs. mass per unit area

The values for lead equivalent vs. mass per unit area determined for approximately 30 protective materials as part of certification based on the European Guidelines for Personal Protection Equipment are shown in ▶ **Fig. 1**. The points near the line represent the materials containing lead. The reduced-lead and lead-free aprons, with a maximum weight reduction of 17 %, are below the line. However, it must be taken into consideration that some lead-free aprons only meet the specified lead equivalent up to 100 kV. At higher tube voltages, the protective effect can be reduced.

In [15] commercially available aprons were examined with respect to weight and protective properties. For lead equivalents between 0.25 and 0.35 mm, only minimal differences in protective effect were seen. Although 0.5 mm aprons provide good protection, the authors feel that they are too heavy based on the associated orthopedic problems.

Back exposure

Depending on the tube voltage and orientation of the phantom used in the phantom measurements [14], the $H_p(10)$ values measured on the back of the examiner were 0.002–0.006 (2–6 permille) of the $H_p(10)$ dose measured on the front of the examiner.

In clinical measurements, the following relationship between $H_p(10)$ back dose and dose area product was determined in various interventions (ERCP, cardiac catheter, PTA, embolization, etc.) on the back of the person working at the patient table:

$H_p(10)_{dorsal} = C_d * DFP\ H_p(10)_{dorsal}$: µSv, *DFP*: Gy*cm².

The protection factor C_d fluctuated between 0.035 (80 kV) and 0.06 (120 kV) depending on the orientation of the examiner to the beam path and the tube voltage. For the dose area product determined in clinical operation from 10 to 300 Gy*cm², the $H_p(10)$ back doses were < 1 to 18 µSv per examination, corresponding to less than 1 mSv per year for a normal workload. In the case of additional protection of the back with 0.125 mm Pb, an annual $H_p(10)$ dose of less than 0.1 mSv was calculated based on the measurements.

The back dose of assistants was also determined. It was approx. 30 % of the back dose of medical personnel working directly at the patient table. The measurements include the fact that assistants occasionally turn around so that their back is toward the radiation source. However, the distances to the radiation source for this group are greater on average than in the case of a location directly at the table.

For CT interventions (puncture, RF ablation), the annual dose was less than 1 mSv for a typical workload in the case of an *unprotected back*. In the case of protection with 0.125 mm Pb, an annual personal dose equivalent $H_p(10)$ on the back of < 0.15 mSv was calculated.

Effective dose-based protection factors

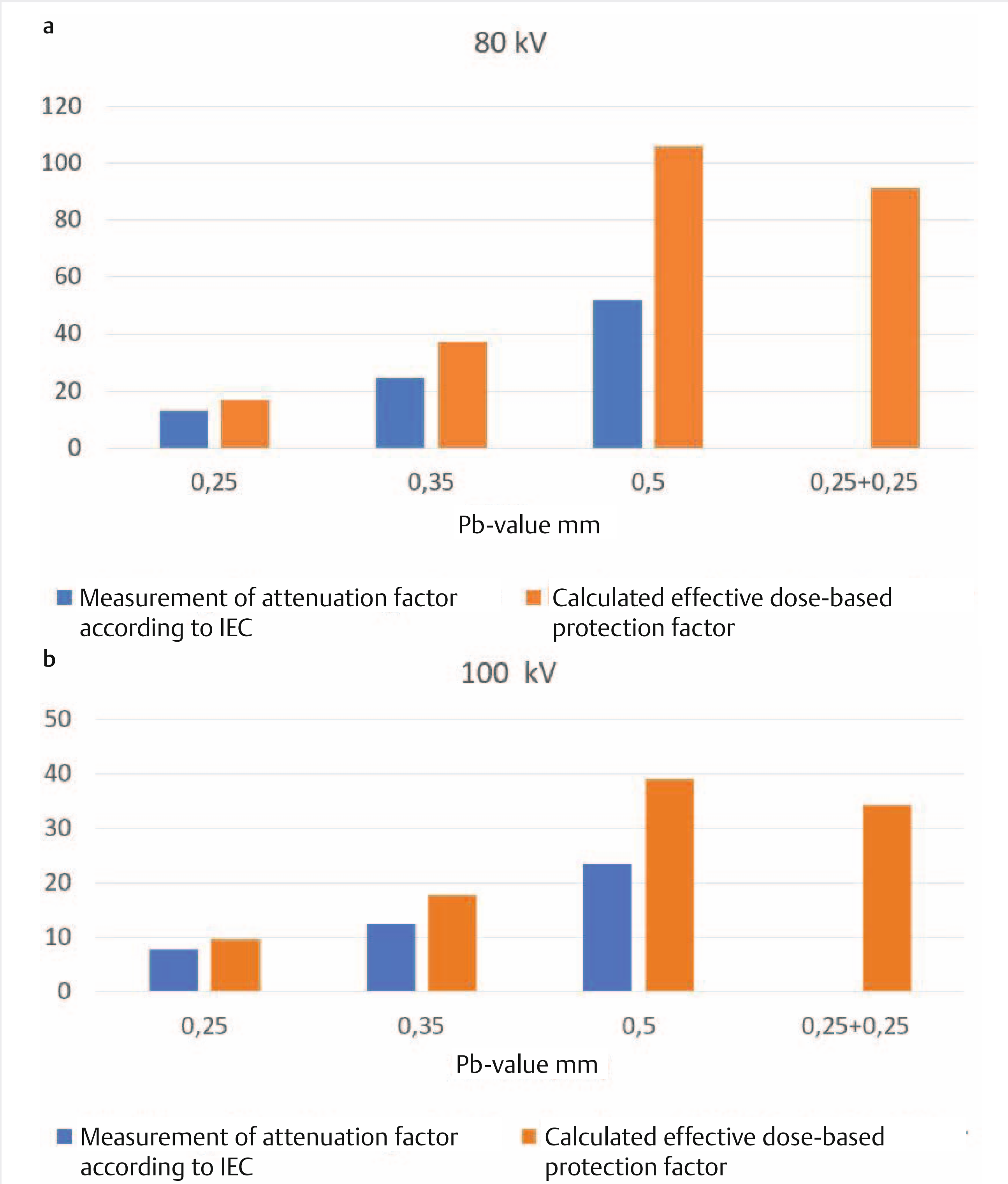
▶ **Fig. 3** shows the effective dose-based protection factors calculated with the Monte-Carlo method in relation to the effective dose compared to the attenuation factors measured in accordance with IEC 61 331–1 on the basis of flat samples irradiated at right angles [10, 11]. The value 0.25 + 0.25 refers to a basic apron with a lead equivalent of 0.25 mm plus a reinforcing layer with a lead equivalent of 0.25 mm, see below. The effective dose-based protection factors have attenuation factors that are up to two times those determined according to IEC 61 331–1.

New protection concept

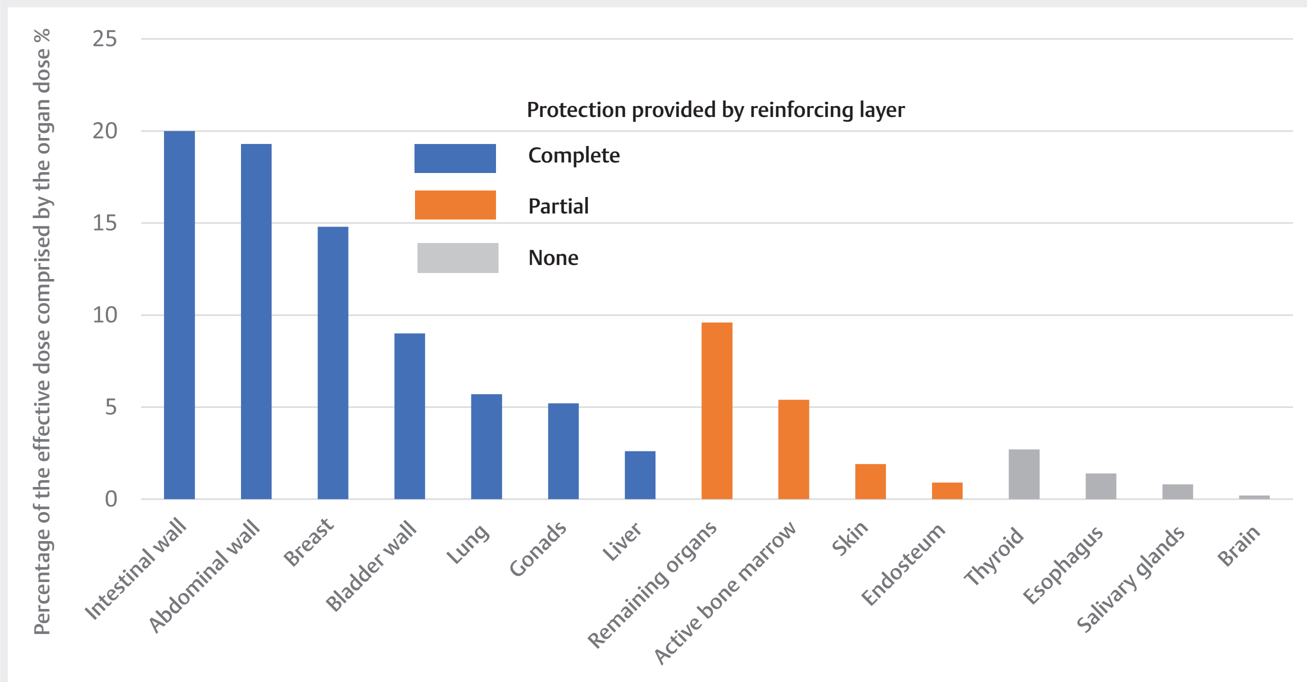
Reinforcing layer

Over 80 % of the effective dose can be attributed to the body region from the gonads up to and including the chest of the person performing the intervention. A reinforcing layer in this region can thus significantly increase the weight-based efficiency of the apron. ▶ **Fig. 4** shows which organs/tissue are completely or partially protected by the reinforcing layer and their percentage of the effective dose. ▶ **Fig. 5** shows the inclusion of the reinforcing layer in a reference model and its effect on the skin dose.

The weight of the reinforcing layer can be compensated by reducing the weight, for example, of the back protection and with a lower lead equivalent of the basic apron. Due to the higher effectiveness of the reinforcing layer in relation to reducing the effective dose, it is associated with a weight advantage.



▶ **Fig. 3** Comparison of effective dose-based protection factors with the protection factors acquired from the measurement according to IEC 61 331–1 using flat samples of the same protective material. The value 0.25 + 0.25 refers to a basic apron with 0.25 mm Pb and an additional reinforcing layer with 0.25 mm Pb.



▶ **Fig. 4** Contribution of the individual organs to the effective dose for a typical workstation situation including interventions and a 100 kV tube voltage. The values relate to the exposure without protective clothing. The color coding indicates whether the organs are completely (blue), partially (orange), or not (gray) covered by the reinforcing layer.

Factors F_{Teff} and the apron weight of front aprons in size M are shown in ▶ **Table 1** for various lead equivalents with and without a reinforcing layer.

Two apron types seem particularly suitable for clinical application:

- Apron for intensive X-ray applications (e. g. interventions)

The apron consisting of a basic apron with a lead equivalent of 0.25 mm and a reinforcing layer with a lead equivalent of 0.25 mm is suitable for interventional applications with an annual dose area product (workload) of 10 000 Gy*cm² and higher (corresponding to approximately 400 ERCPs [16]). The annual effective dose of the examiner without a protective apron is 37.9 mGy with a DAP of 10 000 Gy*cm². With a protection factor of 87 (80 kV) and 34 (100 kV), the annual effective dose would be 0.47 mSv at 80 kV and 1.11 mSv at 100 kV. Therefore, the apron provides very good protection. It is sufficient even in the case of workloads of up to 30 000 Gy*cm²/year as seen in neuroradiology.

The apron offers double the amount of protection compared to the standard 0.35 mm apron with a negligible increase in weight and provides almost the same level of protection as the standard 0.5 mm Pb apron but with a weight reduction of 16 %.

- Apron for brief X-ray applications (e. g. surgery, orthopedics room)

This apron with basic protection with a lead equivalent of 0.175 mm and a reinforcing layer with a lead equivalent of 0.175 mm is suitable for surgeries and other applications with a low dose (e. g. orthopedics, intraoperative X-ray, cardiac pacemaker implantation, etc.). For a typical annual workload of 5000 Gy*cm² at 80 kV, the annual effective dose for the user of this light-duty apron is 0.57 mSv. The protective effect is close to that of a conventional 0.35 mm front apron. However, the weight corresponds to that of an apron with a lead equivalent of 0.25 mm, which is more pleasant when worn for an extended period of time.

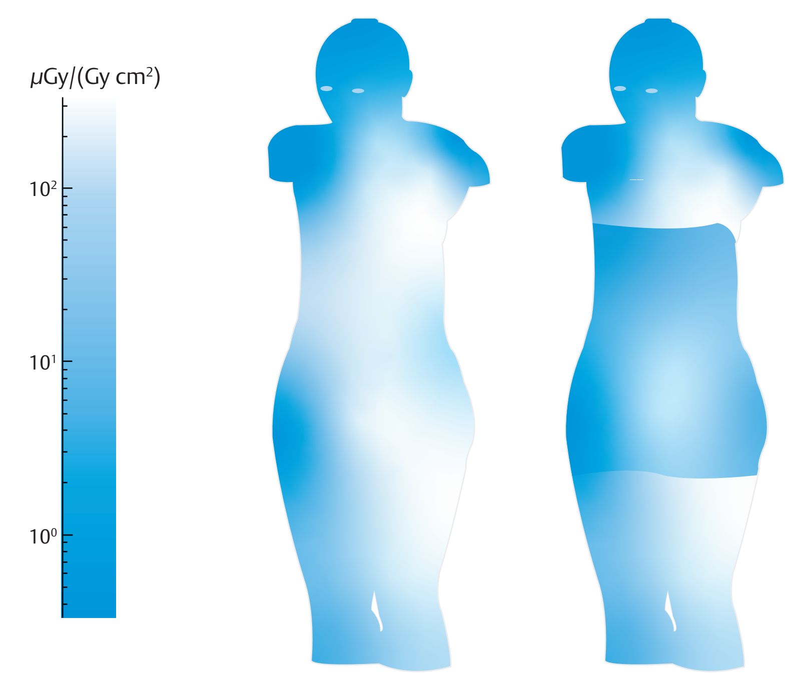
- Organ protection factors F_{Org} [10, 11]

In addition to the effective dose-based protection factors, the corresponding organ protection factors can be taken into consideration: ▶ **Table 2** shows that the average values of the organ protection factors of the organs protected by the reinforcing layer are slightly higher than the effective dose-based protection factor. The apron with the reinforcing layer is about 0.7 kg lighter than the apron with a uniform lead equivalent.

Discussion and conclusion

Protection factor and lead equivalence

The introduction of effective dose-based protection factors provides a completely new perspective with respect to lead equivalence. The protective effect of a 3 D surface – such as a protective apron covering the body – is significantly greater in the case of scatter radiation than that of a flat protective layer with a perpendicular angle of incidence. The parallel fields used in Ref [13] are only conditionally suitable for calculating protection factors for the real situation since the scatter radiation emitted by



▶ **Fig. 5** Visualization of the skin dose distribution using grayscale coding based on the female reference model as the result of the MC simulation. The effect of the reinforcing layer (image on the right) is clearly visible.

▶ **Table 1** Effective dose-related protection factors F_{Teff} for protective aprons at 80 and 100 kV with associated apron weights. A reference weight of 12.6 kg/m² per 1.0 mm Pb (lead-reduced material) was used.

Pb equivalence mm	Reinforcing layer mm Pb	Protection factor F_{Teff} 80 kV	Protection factor F_{Teff} 100 kV	Apron weight for size M (kg)
0,25	–	17	10	2,42
0,35	–	37	18	3,29
0,50	–	106	39	4,31
0,25	0,25	87	34	3,63
0,175	0,175	33	16	2,66

the patient at a short distance from the protective apron has a significantly flatter angle of incidence than parallel radiation, also refer to [10].

Unprotected body parts

In [13] the effective dose-based protection factors for the whole body F_{Geff} including unprotected body parts (extremities, skull) are calculated. Unprotected body parts decrease the protective effect for the whole body. Although the skin and periosteum of the extremities have a low organ weighting factor of only 0.01, they can make a noteworthy contribution in relation to the effective dose percentage of the protected region. Therefore, the whole-body protection factor can be significantly lower than the attenuation factor of the apron when “radiation leaks” which allow scatter radiation to enter are not additionally shielded (▶ **Fig. 6**).

For example, armholes are a classic entry point. The external scatter radiation can penetrate to the shoulder joint and lung tissue or even into breast tissue. Therefore, upper arm attachment pieces and thyroid protection are strongly recommended. Protection of the skull which includes 3–4 % of all active bone marrow [17] seems useful but is difficult to implement in practice. A protective shield positioned above the table with flexible lead strips that can be placed on the patient is an option here. The flexible lead strips greatly increase the effectiveness of the protective shield.

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▶ **Table 2** Organ protection factors F_{Org} calculated for 100 kV tube voltage for the female ICRP reference model. Calculations refer to an apron with uniform 0.5 mm *PbGW* and an apron of 0.25 mm *PbGW* with reinforcing layer 0.25 mm *PbGW*.

Organ	Organ-protection factor F_{Org} for an 0,5 mm Pb apron	Dose reduction %	Organ-protection factor F_{Org} for an 0,25 mm Pb apron with 0,25 mm Pb reinforcing layer	Dose reduction %
Colon	34,8	97,13	34,3	97,08
Lung	43,4	97,70	40,9	97,56
Stomach	36,6	97,27	36,4	97,25
Breast	63,4	98,42	61,5	98,37
Gonads	25,5	96,08	23,1	95,67
Liver	38,5	97,40	38,2	97,38
Ur. Bladder	39,4	97,4	37,5	97,33
Mean	**40,2**	**97,51**	**38,8**	**97,42**
Effective dose protection factor F_{Teff}	**39,1**	**97,44**	**34,3**	**97,08**
Apron weight	**4,31 kg**		**3,63 kg**	

The following measures are needed to achieve the theoretically calculated effective dose-based protection factors F_{Teff} for the whole body:

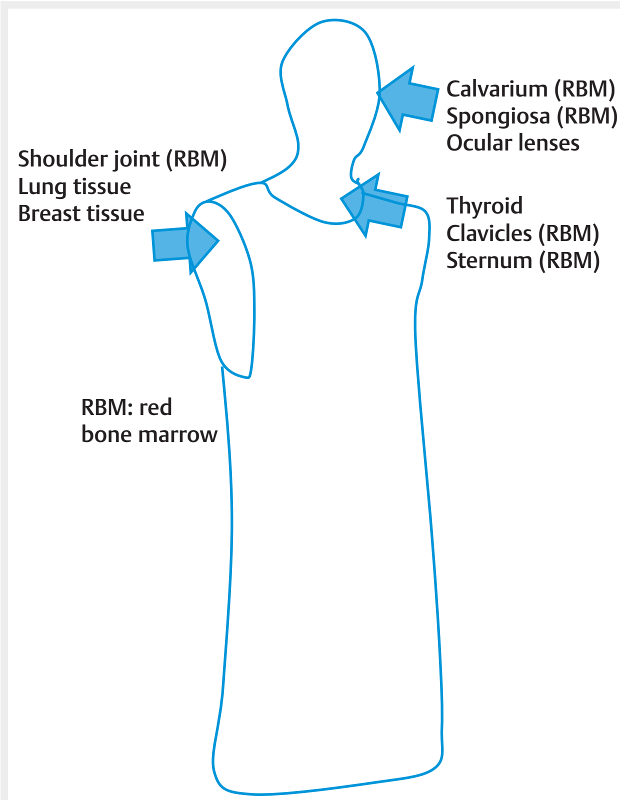
- Protective shield positioned above the table with flexible lead strips (if able to be used)
- Protective shield for the side of the table that extends to the floor (including shielding against backscatter from the floor)
- Thyroid protection
- Upper arm protection for the armholes (particularly lung tissue, breast tissue, shoulder joints)

Since the effective dose-based protection factor depends on secondary conditions, the lead equivalent purely as a value of the materials used is still suitable for classifying protective aprons. In contrast, the effective-dose-based protection factor is more suitable for radiation protection planning, since, for example, it allows calculation of the annual personal dose equivalent.

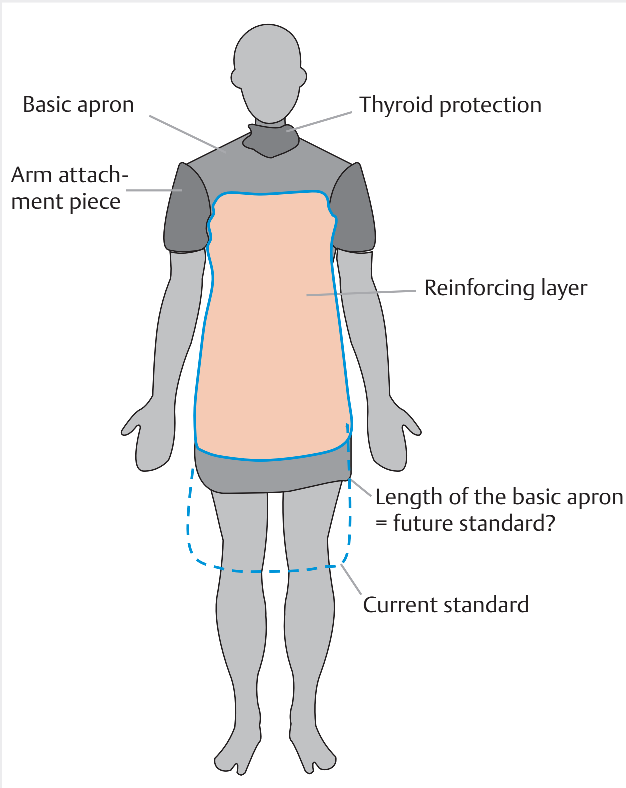
Future apron design

As the studies showed, parts of the current apron design have little effect on the effective dose. Approximately 30 % of the weight of the apron does not have a significant effect on the effective dose. This primarily relates to the back as well as the region from the gonads to the knees. Adults 20 years and older no longer have any active bone marrow from the middle of the femur down [12, 17, 18]. In addition, radiation protection on the side of the patient table is universally used today.

A possible future design for a radiation protection apron is shown in ▶ **Fig. 7**. The basic apron covers the torso from the shoulder to approximately the middle of the thigh. The reinforcing layer (typically inside the basic apron) extends from below the hip joint up to and including the chest. Back protection is not primarily necessary. Back protection with a lead equivalent of



▶ **Fig. 6** Radiation leaks (upper arm/shoulder joint, base of the neck, and skull) should be covered to achieve the highest possible whole-body protection.



▶ **Fig. 7** Possible new apron design with weight reduction of up to 40 % while maintaining the same protective effect.

0.125 mm would be optionally conceivable for weight compensation and to further lower the already very low dose.

Such an apron design is 30–40 % lighter than the conventional apron design and has the same protective effect. If needed, the weight advantage can also be used to increase the protective effect of the apron. However, due to the unavoidable openings in the protective apron, whole-body protection factors greater than 30–50 are hardly possible.

Change of standards

The current manufacturing standards for X-ray protective clothing IEC 61 331–3:2014 [19] and DIN EN 61 331–3:2016 [20] unfortunately do not allow the apron to end below the epiphyses of the hip approximately at the middle of the thigh. As stated above, adults no longer have any active bone marrow there. If it is taken into consideration that protective shielding is already attached to the sides of the patient table, the apron weight can be reduced by 15–20 % without reducing radiation protection. Protection on the sides of the table should be the standard today and be included in the corresponding manufacturing standard as a requirement.

As the results show, back protection can also be greatly reduced since examiners do not trigger radiation with their back turned to the patient. Measurements among assistants also show only very low back exposure.

However, it is important to expand the protective region of front aprons to 60 % of the user's girth at the widest point as currently already required by the manufacturing standard. This effectively blocks radiation with an oblique angle of incidence with respect to the frontal axis as frequently occurs when the examiner turns in the direction of the monitor.

Any new version of the standard should take this new information into account.

Conflict of Interest

The authors declare that they have no conflict of interest.

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