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Original paper

The use of out-of-plane high Z patient shielding for fetal dose reduction in computed tomography: Literature review and comparison with Monte-Carlo calculations of an alternative optimisation technique

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ABSTRACT

When performing CT examinations on pregnant patients, great effort should be dedicated towards optimising the exposure of the mother and the conceptus. For this purpose, many radiology departments use high-Z garments to be wrapped around the patient's lower abdomen for out-of-plane organ shielding to protect the fetus. To assess their current protection efficiency, we performed a literature review and compared the efficiencies mentioned in the literature to Monte-Carlo calculations of CT protocols for which the overall scan length was reduced. We found 11 relevant articles, all of them reporting uterus exposure due to CT imaging performed for exclusion of pulmonary embolism, one of the leading causes of peripartum deaths in western countries. Uterus doses ranged between 60 and 660 µGy per examination, and relative dose reductions to the uterus due to high-Z garments were between 20 and 56%. Calculations showed that reducing the scan length by one to three centimetres could potentially reduce uterus dose up to 24% for chest imaging, and even 47% for upper abdominal imaging. These dose reductions were in the order of those achieved by high-Z garments. However, using the latter may negatively influence the diagnostic image quality and even interfere with the automatic exposure control system thus increasing patient dose if positioned in the primary beam, for example in the overranging length in helical acquisition. We conclude that efforts should be concentrated on positioning the patient correctly in the gantry and optimising protocol parameters, rather than using high-Z garments for out-of-plane uterus shielding.

1. Introduction

Over the 20th century, X-ray imaging has become an extremely useful diagnostic tool in medicine. Since its introduction in the 1970s, computed tomography (CT) has become an indispensable imaging tool within numerous clinical facilities. Recently, due to several technical developments and software innovations, the use of CT imaging has increased to represent a non-negligible proportion of diagnostic examinations using ionising radiation. For example, in 2013, it represented roughly 10% of all X-ray examinations, for a mean collective dose contribution of 70% due to X-ray medical imaging in Switzerland [1].

For any X-ray imaging modality, apart from the primary beam, several other sources of radiation can expose the patient: tube leakage and patient-induced scattered radiation (see Fig. 1). However, the tube leakage is limited by the International Electro-technical Commission (IEC) to a maximum dose rate of 0.1 mGy/h at 1 m from the patient, and will be substantially lower than the patient scatter [2]. Several lead and non-lead (high Z) based protective garments have been proposed to reduce scattered radiation: aprons, skirts and wrap-around drapes. The latter is the most commonly used within radiology suites. Currently, high Z garments used on patients for organ shielding outside the primary field are often proposed to provide some protection from radiation scattered by the patient couch. Indeed, a study by Weber et al., decomposing the different components of scattered radiation in CT, found out that the main component of scatter irradiating the patient is internally produced scatter, and that high Z garments are only efficient against radiation backscattered from the patient couch [3]. This implies that the proper use of these drapes is not to wrap it around the patient but merely to place it between the patient couch and the patient, although many practitioners prefer wrapping the drape around the patient's lower abdomen.

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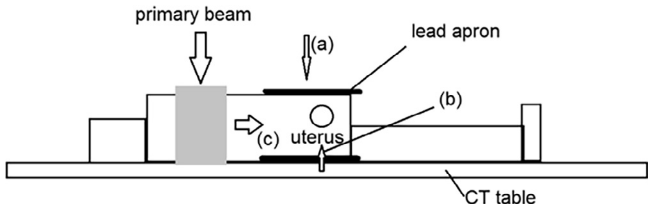

Fig. 1. Schematic depiction of the components of scatter for a chest CT examination using a high Z garment wrapped around the patient's waist. a) External scatter/leakage radiation, b) backscatter from the X-ray table, c) internal scatter.

Fetuses are highly sensitive to ionising radiation [4]. It is therefore of current practice to perform the imaging of pregnant women with more consideration. However, the use of out-of-plane high Z garments in the clinical routine gives rise to many questions within the radiology practice, and its application is quite heterogeneous. For example, the mean European usage rate of high Z garments for pregnant patients was 46.3%, whereas it rose to 94.5% in North America [5]. Furthermore, 25% of practitioners handling high Z garments complained about the weight of these garments, with approximately 20% experiencing occupationally related back pain [5]. Within the current legal framework of all European countries, it is of interest to wonder whether these protection tools are still of any interest, or if they ought to be safely discarded with respect to alternative technical patient protection methods.

The two purposes of this paper were the following: First, we sought to establish a literature review of high Z out-of-plane patient shielding efficiency for uterus dose reduction in CT. Then, we compared the respective efficiencies of the shielding items to simple examination optimisation techniques using a dedicated Monte-Carlo calculation. We will not discuss in-plane garments, as these impair the diagnostic quality, as well as the functioning of the automatic exposure control (AEC) system, as we will detail further on.

2. Materials and methods

2.1. Literature review

We performed a literature search using the PubMed search engine. Search words were: shielding, radiology, computed tomography, uterus, and pregnant patient. Papers published before 2006 (older than 10 years) were discarded, to take into account the recent evolution of CT imaging, mainly automatic tube current modulation and iterative image reconstruction. Papers not citing uterus dose were rejected. Search words were selected based on their link to the topic, and included the following: “uterus”, “fetus”, “X-ray”, “dose”, “exposure”, “computed tomography”, “CT”, “lead”, and “shielding”.

2.2. Monte-Carlo calculations

We performed Monte-Carlo calculations to compare the efficiency of dose reduction when using high Z garments from data gathered from the literature to the dose sparing to the uterus when optimising the CT examinations by reducing the acquired scan length. We used the ImPACT dose calculation spreadsheet [6], version 1.0 (28.08.2009), to simulate standard single-phase CT examinations of the upper abdomen (Fig. 2) and the chest (Fig. 3). ImPACT, developed by a group of British medical physicists, radiologists, and IT specialists, relies on an Excel spreadsheet that allows the user to select the right CT model and acquisition parameters. The calculation of the respective organ doses *per se* has already been performed by the National Radiological Protection Board (NRPB) through 23 series of Monte-Carlo simulations [7]. ImPACT merely works as search engine and corrects the NRPB SR250 results based on specific technical factors collected on the respective CT models implemented in the spreadsheet, and applies the necessary tissue weighting factors based on either the ICRP 103 scheme (the former ICRP 60 scheme is still accessible but is no more in use for these kind of calculations). According to a presentation by E. Castellano at the British CT users group meeting in 2010, the overall error potentially introduced by ImPACT for the calculation of effective dose can reach up to 46%, mainly depending on the scan range, helical over-ranging, patient size, mA modulation (not taken into account by ImPACT) and an intrinsic 7% error margin from the actual Monte-Carlo simulation by the NRPB [8]. The main source of error lies within the definition of the scan range, and can be minimised by accurately measuring the distance between the planned acquisition volume and the uterus, either during the acquisition – based on the scanned projection radiography (SPR).

Since image quality at a given location is intrinsically linked to $CTDI_{vol}$ [9], to optimize the dose while keeping the image quality constant we reduced the respective scan lengths by several cm in steps of one cm, while maintaining the coverage of the organs of interest. The subsequent absorbed uterus doses for each protocol was calculated. The $CTDI_{vol}$ was set to correspond to approximately 10 mGy, which is the diagnostic reference level (DRL) for a standard chest CT in Switzerland [10].

3. Results

3.1. Literature review

We found 11 relevant articles, listed in Table 1[3,11–20]. All of them reported uterus exposure due to CT imaging performed for exclusion of pulmonary embolism (PE). Indeed, the risk of venous thromboembolism (VTE) is increased by the haemodynamic changes during pregnancy, with a rate of 1.72 per 1000 deliveries [21], and is the sixth leading cause of maternal mortality in the US, with 20 to 30% of peripartum deaths due to PE [22]. It is thus the main indication of chest CT for pregnant women. Uterus doses, taken as a surrogate for fetal exposure for first-trimester pregnancy, ranged between 60 [12] and 660 [11] μGy per examination. High Z garments, wrapped around the waist of the woman, allowed for a relative absorbed dose reduction between 20 [12] and 56% [15] to the uterus.

3.2. Monte-Carlo calculations

Tables 2 and 3 show the results obtained by our Monte Carlo calculations for the dose sparing to the uterus for upper abdomen and chest CT respectively. Reducing the scan length by one to three centimetres can potentially reduce uterus dose up to 24% for chest imaging and even 47% for upper abdomen imaging. This dose sparing is in the order of that achieved by high Z garments wrapped around the patient (between 20% and 56% dose sparing). Reducing the scan length by 1, 2 or 3 cm allows for an absolute uterus dose reduction of respectively 400, 700 and 900 μGy for upper abdomen CT imaging, while a 3 cm length reduction in a chest examination will reduce the uterus dose by about 17 μGy (Tables 2 and 3).

4. Discussion

The efficiency of high Z garments to protect the uterus of pregnant patients is highly sensitive to its actual positioning. According to the extensive modelling study by G. Iball et al. [12], there seems to be a linear relationship between the uterus-to-garment edge distance and the uterine dose. As such, when the garment edge is placed at the same position as the uterus along the main patient axis, the dose reduction is about 10%, whereas it linearly increases when sliding the garment closer to the scanned volume (60% decrease with garment edge 22.5 cm above the uterus), with a uterus dose of 63.3 μGy without any high Z garment. This seems to be in correspondence to a further measurement in that same study, where it is shown that the uterine dose increases

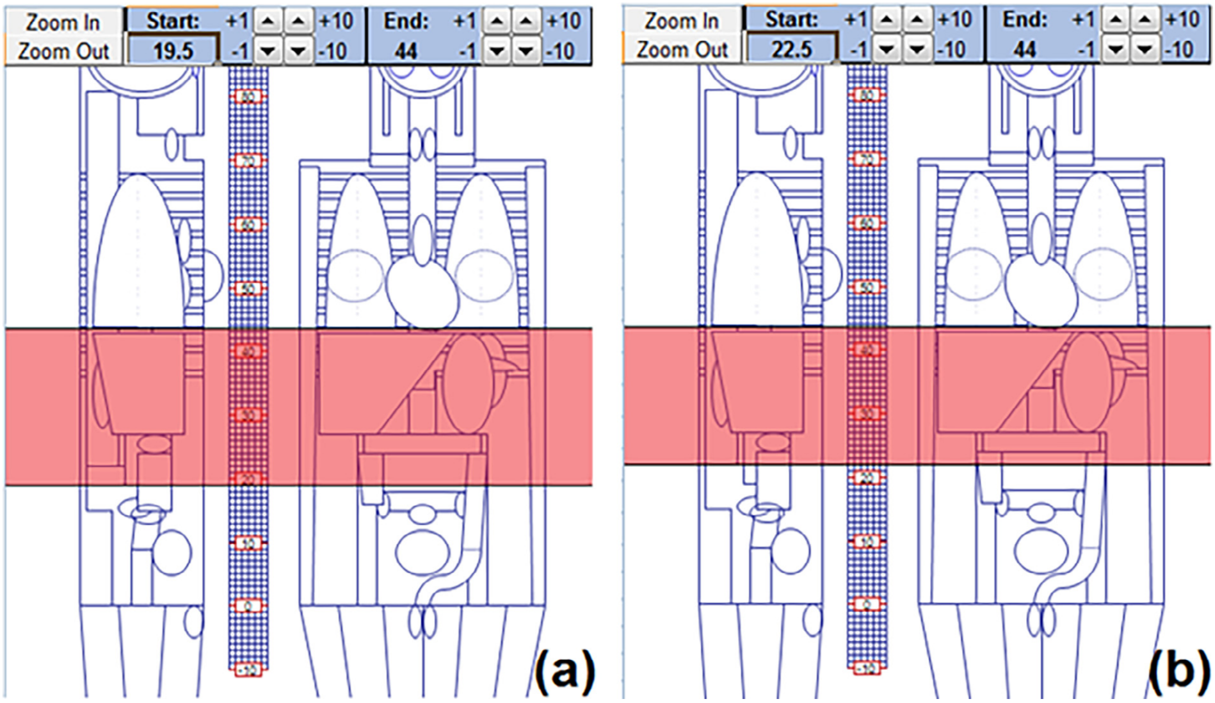

Fig. 2. Screenshot of the ImPACT GUI for upper abdomen CT. (a) acquisition volume before scan length reduction, (b) acquisition volume after reducing the scan length by 3 cm under the liver.

exponentially with scan edge being moved closer to the edge of the garment, kept constant at 15 cm above the uterus with respect to the main patient axis.

However, both experiments resulted in a partial irradiation of the anatomy covered by the garment. This presents several negative consequences. First, as is shown in a study by Dauer et al. [23], a high Z garment (in the present case a male gonadal shield in the primary beam) leads to massive photon starvation artefacts, that render the images generated at those locations hardly useful for any diagnosis. Furthermore, the vast majority of adult CT protocols are based on

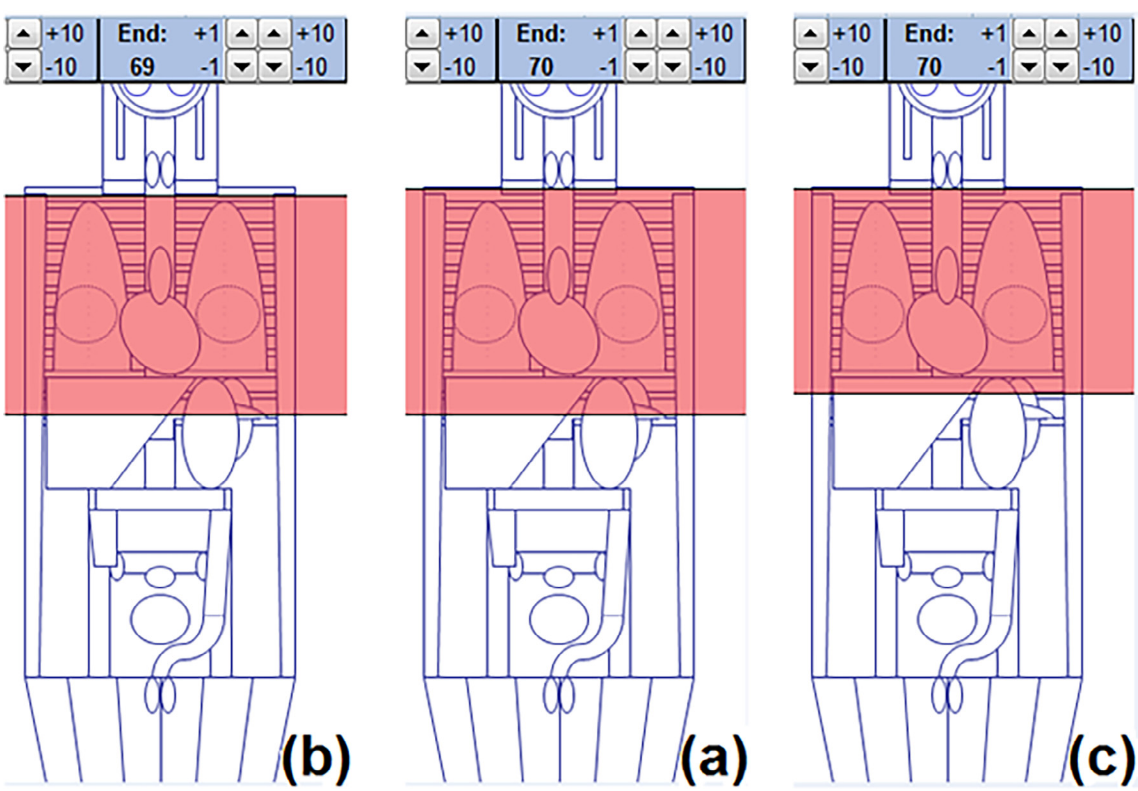

Fig. 3. Screenshot of the ImPACT GUI for chest CT. (a) Acquisition volume before scan length reduction, (b) acquisition volume after reducing the scan length by 1 cm above the lung apex, (c) acquisition volume after reducing the scan length by 3 cm under the lung base.

Table 1
Papers published in the literature, addressing the potential uterine doses and dose reductions due to CT examinations.

Authors	Year	Type of examination	Type of study	Type of dosimeter	Comments	Reference uterus/foetal dose	Efficiency
Hurwitz et al.	2006	PA, appendicitis, renal stones	Anthropomorphic phantom	TLD + MOSFET	Uterus dose, no use of garments	Between 240 and 660 µGy	N/A
Iball et al.	2007	PA	Anthropomorphic phantom	Ionisation chamber	Systematic testing of acquisition parameters (kV, mA, scan length, garment position)	Between 60 and 500 µGy	Average: −39.7% kVp: [−33%–47%] (0.7 mmPb) Pitch: [−41%–45%] (0.7 mmPb) Garment posterior: −20% Garment around: −40% mAs: linear dose variation Rotation time: no sign. change Collimation: no sign. change
Iball et al.	2008	PA	Anthropomorphic phantom	Ionisation chamber	Testing of different garment materials, proposal of a predictive irradiation model	Between 30 and 190 µGy	Between −40% and −55%
Palmer	2008	PA	Anthropomorphic phantom	TLD	MSc thesis	~210 µGy	−56% (0.7 mmPb)
Doshi et al.	2008	PA	Anthropomorphic phantom	Unknown	–	Between 60 and 230 µGy	mA modulation: −10% High Z garment: −35% 5 cm shorter scan length: −56%
Niemann et al.	2010	PA	Literature review	N/A	Uterus dose due to CT and nuclear medicine for pulmonary embolism	Between 13 and 26 µGy (early pregnancy) Between 60 and 100 µGy (late pregnancy)	N/A
Danova et al.	2010	Chest CT	Anthropomorphic phantom	TLD	–	~65 µGy	High Z garment posterior: −26% High Z garment around: −34%
Iball et al.	2010	CT	Worldwide survey	N/A	Questionnaire for radiographers	N/A	N/A
Iball et al.	2011	Chest CT	Anthropomorphic phantom	TLD	Estimated dose savings for multiple organs	N/A	−35%
Iball et al.	2011	Chest CT	Local survey	N/A	Radiographers alternatively playing the role of the patient	N/A	N/A
Weber et al.	2015	CT	CTDI phantom	TLD	Decomposition of the scatter components	N/A	N/A

Table 2
Technical parameters simulated for the chest CT examination.

Parameters	Length [cm]	Uterus dose [μGy]	Dose reduction	Dose reduction in literature due to high Z garment
$CTDI_{vol}$: 10.4 mGy	32	39	–	Between −20% and −56%
Tension: 120 kV	31 (top)	39	0%	
Current: 200 mA	29 (bottom)	22	−24%	
Pitch: 1.375				
Rotation: 0.75 s				
Collimation: 40 mm				

Table 3
Technical parameters simulated for the upper abdomen CT examination.

Parameters	Length [cm]	Uterus dose [mGy]	Dose reduction	Dose reduction in literature due to high Z garment
$CTDI_{vol}$: 10.4 mGy	24.5	1.9	–	N/A
Tension: 120 kV	23.5	1.5	−21%	
Current: 200 mA	22.5	1.2	−37%	
Pitch: 1.375	21.5	1.0	−47%	
Rotation: 0.75 s				
Collimation: 40 mm				

automatic exposure control (AEC). Schematically, the information obtained by the SPR, performed before the data acquisition, is used for the scanned volume planning. It uses the information of patient's attenuation along the main patient couch axis and/or in both postero-anterior and lateral directions, and plans the X-ray tube current accordingly to achieve a pre-defined noise level across the subsequently reconstructed images, independently of tissue absorption [24]. This implies that such high Z garments, when used, have to be kept outside the primary field, to guarantee images of good diagnostic quality, but also avoid a steep increase in patient dose rate when the highly absorbing garment is found to be in the primary field. Moreover, even if the garment is left outside the scanned volume, scan lengths (in helical acquisition) are extended on both ends due to over-ranging, a side effect of data interpolation for image reconstruction in helical acquisition, which is the case for practically all scans nowadays [25]. This implies that organs right next to the planned acquisition volume might be irradiated by the primary beam, even if this exposure will not lead to any reconstructed images. This holds true if the protective garment is placed right next to the planned volume. Unfortunately, some CT manufacturers have introduced, in addition to SPR-based AEC, 'on-the-fly' dose rate correction based on the actual dose rates measured directly on the CT detectors during the acquisition [26]. Due to this added feature, the dose rate might be unknowingly increased locally, thus increasing scattered radiation inside the patient and annihilating the desired effect of the garment.

Additionally, the efficiency of increasing high Z thickness seems to quickly 'saturate'. Indeed, as described by Iball et al. [12], efficiency rapidly increases between 0 and 3.5 mmPb, and seems to remain constant above these values. As such, too heavy garments may be detrimental to patient comfort and operator back constraints [18,20], with no significant gain in dose reduction efficiency.

Furthermore, the increase in the hypothetical lifetime risk of cancer or leukaemia induction in the conceptus is of the order of 1 in 170 after a 100 mGy exposure (which is between two and three orders of magnitude above the mentioned dose sparing), whereas the overall risk of contracting cancer during a lifetime is about 1 in 3, 1 in 5 being the risk for a fatal malignancy [27]. Caution may be taken when reducing the scan length for a suspicion of PE, as sudden onset of lower chest pain may also be caused, although rarely, by adrenal haemorrhage, which can even become life-threatening [28]. As adrenal spontaneous haemorrhage has been recorded as a complication during pregnancy, which can mimic PE symptoms, the spearing of few centimetres in the scanned volume could be dangerous.

Finally, since the demand in CT examinations is steadily increasing, there is a growing pressure on medical staff to optimise the time the patient spends within the radiology department. In opposition to MRI imaging, the acquisition time of a single – or multiple – CT phase(s) is a mere matter of seconds [29]. As such, there is often limited time dedicated per CT procedure, implying a pertinent choice among the means of optimisation at the disposal of the medical staff. Thus, a proper positioning of the high Z garments for an efficient protection will consume time that could be spent to guarantee the overall patient care.

One limitation of our study is not addressing the topic of in-plane bismuth protections. However, as for iterative reconstruction, organ-based modulation is sufficiently widespread in current CT imaging that those devices, prone to inducing photon starvation artefacts, are no longer deemed relevant for the protection of in-plane anatomy [30,31].

Furthermore, although the ImPACT phantom is the mathematical MIRD phantom, thus far from actual patient anatomy, the usefulness of the calculation spreadsheet lies in the fact that it is easy to use, and widely available. More consequent Monte-Carlo simulation environments, using for example voxelised phantoms such as *Golem* [32] and *Laura* [33] from the Helmholtz Zentrum München, may be more accurate in terms of specific organ doses, but need a profound knowledge of Monte-Carlo simulation environments, along with a tremendous calculation power. ImPACT offers a quick yet quite precise solution for gross dose estimations to different organs. We used the ImPACT spreadsheet as an easily accessible calculation method for relative efficiency of dose reduction techniques linked to the shortening of the scan length, even though a dedicated simulation environment using more realistic phantoms, such as MCNP or Geant 4, would provide more accurate absolute results.

Finally, we used uterine dose as a surrogate for fetal dose, since the anthropomorphic phantom used by ImPACT is not suited for pregnancy simulation. For late pregnancy, other organs, such as the liver or the transverse colon, may be taken as a surrogate for fetal dose. However, after the 25th week of pregnancy, the impact of X-ray dose to the fetus is lessened, and in utero tissue effects, such as IQ impairment or deformities, are no longer of concern. Since CT doses are, overall, quite low with respect to the threshold of tissue effects on the fetus (i.e. around 100 mGy of absorbed dose), the consequences of large error margins on uterine and/or surrogate organ doses is deemed less consequential than, for example, calculation errors within radiation therapy dose calculations.

5. Conclusion

The expected dose savings from the use of high Z garments may be counterbalanced by the optimisation of scan lengths, a parameter immediately accessible by the operator of the unit. Although dose savings from high Z garments might seem high (up to 56%), the absolute uterine doses delivered outside the primary field are already quite low (a few hundred μGy) per examination. In comparison, the efficiency in terms of dose reduction by correctly selecting the scan length is similar to the exposure reduction due to high Z garments, without the potential adverse effects, especially when using on-line dose rate adjustment.

To summarise, a thorough justification of the examination [34], optimal patient positioning to fully take advantage of the bow tie filter and AEC, the choice of an appropriate clinically relevant image quality level and the strict limitation of the scan range will yield uterine dose sparing in the order of those expected for well-placed high Z garments, without the latter's downsides. Patient exposure savings by means of optimising the examination length and dose are probably much less time- and energy-consuming. The current main optimisation paradigm is adapting the acquisition parameters to the actual clinical demand and clinical task [9], that allows for an objective quantification of image quality gain (or loss) with respect to patient exposure, especially when using low-dose protocols. Dose sparing by high Z garments, albeit coming 'free of charge', is only to be expected if no other relevant technical or clinical parameter might be optimised, and if no garment is ever placed in the primary field of view, including the over-ranging in CT imaging. The current status of CT technology allows for drastic dose reductions by correctly using the AEC systems and/or increasing the level of iterative reconstruction. For the latter, one should take care as to not finally lose any diagnostic information, especially for low contrast detectability [9].

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