Organ and effective dose reduction in adult chest CT using abdominal lead shielding

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Objectives: The purpose of this study was to evaluate and compare organ and effective dose savings that could be achieved using conventional lead aprons and a new, custom-designed shield as out-of-plane shielding devices during chest CT scans.

Methods: Thermoluminescent dosimeters were used to measure doses throughout the abdomen and pelvis during CT scans of the chest of a RANDO phantom. Dose measurements were made with no shielding, with lead aprons and with the new shield around the abdomen and pelvis in order to quantify the achievable organ and effective dose reductions.

Results: Average dose savings in the 10 phantom sections ranged from 5% to 78% with the highest point dose saving of 93% being found in the mid-pelvis. When shielding was used, the maximum measured organ dose reduction was a 72% dose saving to the testes. Significant dose savings were found throughout the abdomen and pelvis, which contributed to an effective dose saving of 4% that was achieved over and above the dose savings obtained through conventional optimisation strategies. This could yield significant population dose savings and reductions in collective radiation risk.

Conclusion: In this study significant organ and effective dose reductions have been achieved through the use of abdominal shielding during chest CT examinations and it is therefore recommended that out-of-plane patient shielding devices should be used for all chest CT scans and potentially for every CT scan, irrespective of body part.

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Good radiographic practice aims to ensure that patient radiation dose from any examination is kept as low as reasonably practicable (ALARP) [1] as long as the image quality is consistent with the intended purpose of the examination. There are many steps that can be taken in order to reduce the radiation dose on a patient-by-patient basis. One such method is to place radiation-absorbing material, usually in the form of lead rubber shielding, onto the patient surface, outside of the anatomy of interest. Shielding in this manner has been used in dental and conventional radiology as well as fluoroscopy and has been shown to yield significant dose savings [2–7]. This technique, referred to as “out-of-plane” shielding, has also been advocated in CT for protection of the breast and thyroid [8–12]. However, the main use of such shielding has been in protecting the foetus of pregnant patients undergoing head, neck, chest or extremity CT scans. There has been uncertainty whether or not such shielding results in a decrease or increase in the foetal radiation dose due to the potential for increased internal scatter from the shields. Hidajat et al [10] reported no reduction in the dose to the uterus and ovaries when a thin lead shield was used during a scan of the upper abdomen. This, along with further anecdotal evidence, has caused debate over the effectiveness of out-of-plane shielding in CT.

In recent years a number of papers have shown that abdominal shielding yields foetal dose reductions of approximately 35% in both early and late stage pregnancy when patients undergo chest CT [13–15]. Despite this evidence, out-of-plane shielding has not been used regularly in CT scanning even though the use of such shielding has no effect on the quality of the images produced.

Recent publications have brought the issue of radiation dose in CT to the forefront of thinking in the radiology community. In late 2009 Smith-Bindman et al [16] showed that for each examination type there was an average 13-fold variation between the highest and lowest radiation doses from standard CT scans in four hospitals in the San Francisco Bay Area, CA. Further analysis showed that the risk of cancer induction from CT scans was highest for coronary angiography scans of 20-year-old women where 1 cancer could potentially be induced per 150 patient examinations.

Concern was also expressed following the publication of Berrington de Gonzalez et al [17], who sought to quantify the number of cases of cancer that could be attributed to CT scanning in the United States during 2007. It was estimated that 29 000 cancers could be related to CT scans of which 14 000 resulted from abdomen/pelvis scans, 4100 resulted from chest scans, 4000 resulted from head CT and a further 2700 from chest CT angiography. Given the rapid development in scanning technology it is likely that the number of scans performed in 2008 and 2009 is higher than the reported figures of 70 million CT scans for 2007 and, as such, the

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number of cancers induced could be greater than the 29 000 figure for 2007.

The advent of multislice CT (MSCT) has increased the range of examinations that can be performed, and as such Fazer et al [18] now estimate that in the United States approximately 50% of the collective effective dose resulting from medical procedures is attributable to CT scanning. Similarly in the UK approximately 47% of the collective dose from medical procedures is attributable to CT scanning [19].

Aims of this work

The aim of this study was to assess the organ and effective dose reductions provided by conventional lead aprons and a new shielding device when placed around the abdomen and pelvis of a non-pregnant phantom during standard chest CT scans. The new shielding device (ShieldAll, Rothband Ltd, Rossendale, UK) has been designed to provide differential attenuation around the patient and to wrap around patients of all shapes and sizes. Use of such a device was proposed by Iball et al [14] and was shown to yield up to 99% of the dose savings that could be achieved by using conventional lead aprons to provide a consistent level of attenuation all around the patient.

Method

Phantom preparation

A male RANDO phantom (Alderson Research Laboratories, Stamford, CT) was used in this study which represents a 70 kg, 1.7 m tall adult male and consists of 36 transverse sections, numbered craniocaudally, each of which is 2.5 cm thick. The abdomen and pelvis of the phantom was loaded with 286 thermoluminescent dosimeters (TLDs) (LiF TLD100; Global Dosimetry Solutions Inc, Irvine, CA) on a three-dimensional "alternate hole" matrix, such that both within the phantom slice and along the length of the phantom alternate holes contained either a TLD or were filled with a plug of the phantom material. The TLDs were loaded into sections 25–34, which cover the abdomen and pelvis region, and a further 14 TLDs, which were not inserted into the phantom, were used as controls; as such 300 TLDs were used for each scanning regime. The identification number for each TLD was recorded on a three-dimensional grid system that matched the holes in the RANDO phantom.

Scan protocol

A Siemens Definition dual-source CT scanner (Siemens AG, Erlangen, Germany) was used for all of the scanning in this study. The scanner was used in single-source mode using one of the standard chest scanning protocols from our institution, with only minor modifications; details of the scan protocol are given in Table 1.

A helical scan protocol was chosen in order to be most clinically representative even though the overscan required to enable reconstruction of images of the whole lung field would bring the inferior edge of the scanned volume closer to the region in which dose measurements were to be made. The CARE Dose 4D automatic exposure control (AEC) system was deactivated in order to minimise any variability in the mAs values provided by the scanner and therefore improve the reproducibility of the dose measurements across the three sets of measurements.

The effective mAs value used for this study was increased from the clinically used value of 100 mAs to 150 mAs in order to reduce the number of scans required to obtain doses above the TLDs' minimum detectable level of 0.2 mSv. TLDs with a lower minimum detectable dose were not used in this study due to their high cost and the large number for TLDs required for this work. All dose calculations were linearly scaled to the clinically used value of 100 mAs.

In order to determine the effectiveness of the protection afforded by the shielding products three sets of scans were performed: (1) with no lead shielding in place, (2) with both parts of conventional 0.35 mm Pb equivalent lead aprons on both the anterior and posterior of the phantom (*i.e.* 0.7 mm Pb around the full circumference of the phantom) and (3) with a new shielding device around the phantom.

The new shielding device is constructed from varying thicknesses of lead rubber; use of such a device was proposed by Iball et al [14] and was shown to yield up to 99% of the dose savings that could be achieved by using the same thickness of lead all around the patient. This new device has been designed in such a way that the weight placed on the anterior side of the patient is reduced as a greater thickness of lead is used on the posterior side of the patient while the overall level of radiation protection is equivalent to 0.7 mm Pb around the whole of the patient. The weight placed directly on the patient's anterior side is in the range 1.6–2.4 kg compared with 4.9 kg for a conventional 0.35 mm Pb apron.

Table 1. Scan protocol used for all scans of the RANDO phantom

Tube voltage (kV)	Effective mAs	Rotation time (s)	Beam collimation (mm)	Image slice thickness (mm)	Pitch	Displayed CTDI vol (mGy)	Scan length (cm)	Total scan time (s)
120	150	0.5	64 × 0.6 acquisition=19.2 mm as the z-axis flying focal spot is used	5.0	1.2	10.82	30	7.32

The scan protocol was based on one used in our institution; the only changes were an increase in the effective mAs from 100 mAs to 150 mAs (in order to reduce the required number of scans) and deactivation of the CARE Dose 4D automatic exposure control (AEC) system (in order to eliminate any variability in the mAs values delivered by the AEC system and therefore improve the reproducibility of the dose measurements).

For the scans without lead, 35 helical runs were performed. For the scans with both the lead aprons and the new device an estimate was made of the maximum dose reduction that would be expected at the phantom's caudal boundary and this information, along with the minimum dose recorded in the first set of scans, was used to determine the required number of scans with the lead shielding. As such, in these two situations, 45 scans were performed.

For each of the 3 scan regimens the scan volume extended from the centre of phantom section 10 (lung apices) to the centre of section 22 (lung bases) which yielded a scan length of 30 cm. The superior edge of the lead shielding was placed at the position of the lower costal margin, which corresponded to the boundary of phantom sections 24 and 25. Thus the shielding was positioned 6.25 cm below the inferior edge of the reconstructed area. A scan projection radiograph of the RANDO phantom complete with lead shielding is shown in Figure 1. The scan volume is clearly denoted by the pink borders.

Calculation of dose savings

The TLD data allowed simple comparisons of point doses to be made for the three scanning situations. It was therefore possible to calculate point dose reductions and average dose reductions in each phantom section for the

Figure 1. A scan projection radiograph of the RANDO phantom obtained prior to the scans with the lead shielding in place. The extent of the helical scan is shown by the pink borders.

two situations when lead shielding was used. A cubic spline interpolation was used to calculate the dose in the positions between the TLDs in order to give a more comprehensive dose map in three dimensions.

The method of Scalzetti et al [20] was used to calculate doses to organs that fell entirely, or partially, within the abdomen and pelvis of the RANDO phantom for the three sets of scans. Scalzetti et al identified which dose measurement points in a male RANDO phantom correspond to 24 compact organs that are of importance for patient dosimetry. For each critical organ of interest in this study the dose sampling points identified by Scalzetti et al were supplemented by neighbouring points that were identified as lying within the organs of interest based on the organ distribution as shown in Moeller and Reif [21].

The percentage of total skin area, bone surface and red bone marrow for each slice of the male RANDO phantom has been provided by Huda and Sandison [22]. The dose measurement positions throughout the sections of interest that corresponded to bone surface were easily identified and thus for each section an average bone surface dose was calculated. Using the fraction of the total body bone surface in each of the 10 phantom sections, as provided by Huda and Sandison [22], and the known bone surface dose it was possible to calculate first the bone surface dose for each of the three sets of scans and second the change in the total body bone surface dose when lead shielding was used. In this way, the change in the whole body bone surface dose was weighted according to the percentage contained within the shielded area. The changes in the skin and red bone marrow doses were calculated in the same way.

The effective dose resulting from the unshielded chest scan using the Siemens Definition scanner was evaluated using the ImPACT CT Dosimetry spreadsheet, v1.0.2 (www.impactscan.org/ctdosimetry.htm; downloaded Nov 16 2009) and the International Commission on Radiological Protection (ICRP) 103 dosimetry system [23]. CT dose index (CTDI) measurements performed by the authors on the Siemens Definition scanner allowed this scanner to be matched to the Philips 305N (GE3, no Cu) scanner, operating at 120 kV; this scanner already exists in the ImPACT CT Dosimetry spreadsheet.

The organ doses that were calculated using the ImPACT spreadsheet were adjusted by the percentage reductions in dose that were found for each of the organs of interest in this study and these adjusted organ doses were then entered back into the effective dose calculations. In this way the percentage reduction in the effective dose with shielding in place was calculated.

Results

Dose savings per phantom section

The average dose per scan within each phantom section, for each of the three sets of scanning, is shown in Figure 2.

Without lead shielding in place, the average dose per scan decreased with distance from the inferior edge of the scan volume. With lead shielding in place the decrease was more rapid, especially at greater distances

Figure 2. Average dose per scan for each section within the abdomen and pelvis of the RANDO phantom for the three sets of scans that were performed. Error bars represent two standard errors about the mean for each section. The dose values are presented on a log scale.

from the scan volume. Statistically significant differences, at the 95% confidence level, were found between the values of mean dose in each phantom section measured for both sets of shielded scan *vs* the scans without lead ($p < 0.0001$, Kruskal–Wallis ANOVA (analysis of variance)). However, there was no statistically significant difference between the mean dose values for scans with the conventional aprons and the new shield ($p = 0.499$, Kruskal–Wallis ANOVA).

The dose distribution within each section of the phantom for the three sets of scans is shown in Figure 3.

The average dose per scan within each section of the RANDO phantom for the scans without lead shielding, along with the maximum point dose savings and the average dose saving within each phantom section for the scans with the two shielding solutions are shown in Table 2.

The maximum point dose saving that was found in the area protected by the shielding devices was 93% which was found in the lower pelvic region (phantom section 34). The average dose savings per section of the phantom ranged from -6.5% (*i.e.* 6.5% increase in dose) to 77.6%.

Organ and effective dose savings

13 organs were identified as lying partially or completely within the area protected by the shielding devices; the dose savings for each of these organs are presented in Table 3.

For scans with the new shield in place the maximum organ dose saving was found for the testes (71.7%), which is the organ furthest from the scan volume. For the kidneys, which were only partially shielded by the protective devices, the organ dose saving was only 3.7% since the shielding only affected the caudal part of the kidneys. The most radiosensitive organ fully in the protected area, according to ICRP 103 [23], is the colon,

which has a tissue weighting factor of 0.12; the measured dose reduction to the colon was 33.2%. The reduction in the dose to the uterus with the new shield in place was 35.4% and was 42.1% with the conventional aprons; this agrees well with the value of 39.7% found by Kennedy *et al* [13] using a Siemens Sensation 16 scanner.

When calculating the effective dose the gonad dose reduction was taken as the arithmetic mean of the dose saving to the ovaries (24.9%) and testes (71.7%); as such, this averaged gonad dose reduction was 48.3%.

The effective dose for this scan, as calculated using the ImPACT CT Dosimetry spreadsheet, was 6.54 mSv. When the calculated organ dose savings that were achieved though the use of lead shielding were taken into account the effective dose from the chest scan was reduced by 4% to 6.28 mSv.

Discussion

It can be seen from Figure 2 that for the scans with lead shielding in place the average dose per section decreases in a purely exponential manner with increasing distance from the bottom of the scan volume. This indicates that the measured dose is almost entirely due to internal scatter from the scan volume. However, for the scans with no lead shielding in place the relationship is clearly a 2-part function, as shown by the change in the gradient of the line at section 29 (17.5 cm from the scanned volume). This shows that the scatter dose is originating from more than one source, *i.e.* internal and external scatter. The change in the dose gradient at section 29 shows that beyond this point external scatter begins to dominate over internal scatter whereas before section 29 the reverse is true; it is for this reason that the most significant dose savings are found beyond section 29. These findings confirm the validity of the model proposed by Iball *et al* [14], which showed that the dose

Figure 3. Dose distributions within each section of the abdomen and pelvis of the RANDO phantom for the chest CT scans. The left-hand column shows the dose distribution without lead shielding, the dose distribution with conventional lead aprons is shown in the second column, the third column shows the distribution of dose with the new shield and the right hand column shows CT images from the centre of each section of the RANDO phantom. White represents the highest dose; dark blue represents the lowest dose.

measured beneath conventional lead aprons resulted from internal scatter, external scatter and secondary internal scatter (*i.e.* scatter back from the lead aprons).

In the phantom section closest to the scan volume, small increases in the average dose per scan were noted when both shielding devices were used. It is thought that these small increases in dose are due to the uncertainties in the positioning of the TLDs from one scan series to the next along with the exact positioning of the scan volume relative to the anatomy of interest. At this point in the phantom the dose gradient along the z-axis is at its greatest and as such any slight change in the position of the TLD within the hole would yield a relatively large percentage change in the measured dose. It is also possible that some of the observed

increase is due to secondary internal scatter from the shielding devices as the dose increases were observed for all scans with shielding in place.

Kennedy et al [13] have previously shown that the level of protection afforded by lead shielding is highly dependent on the positioning of the shield relative to the scan volume. The largest dose reductions were found when the superior edge of the shielding was aligned with the inferior edge of the scan volume. This may, however, be difficult to achieve in clinical practice, as the radiographic staff cannot run the risk of the lead shielding extending into the scan volume. Therefore, in this study, a small gap was present between the inferior edge of the scan volume and the superior edge of the shielding.

Table 2. Average dose per scan for each section of the RANDO phantom with no lead shielding in place and the maximum and average dose saving per section for the scans with the lead aprons and new shielding device (a negative value of dose saving corresponds to an increase in dose)

Section number	Distance from inferior edge of scan (cm)	No lead	Lead aprons		New shielding device	
		Average dose per scan (μ Gy)	Maximum point dose saving (%)	Average dose saving (%)	Maximum point dose saving (%)	Average dose saving (%)
25	7.5	2444	19.0	-6.5	29.3	-4.8
26	10.0	1544	53.4	6.5	46.0	5.1
27	12.5	978	41.0	16.1	47.5	10.8
28	15.0	624	61.5	25.3	42.3	18.7
29	17.5	397	78.0	28.4	68.2	29.2
30	20.0	289	81.3	47	75.6	41.8
31	22.5	207	86.1	55.3	83.3	50.6
32	25.0	147	88.1	60.8	86.5	57.3
33	27.5	112	90.6	71	89.0	65.3
34	30.0	92	93.1	77.6	91.9	73.6

As shown in Figure 3, the dose savings at the periphery of the phantom were higher than in the centre of the phantom. For example, in section 34, the average dose reduction for the 25 holes closest to the skin surface was 81.3%, whereas for the central 25 holes the dose saving was 65.9%. This results in large reductions in skin dose throughout the abdomen and pelvis. Although the dose savings to the skin are high only 16.7% of the body's total skin area is contained within the slices of interest and it is for this reason that the whole body skin dose saving was only 9.3% with the new shield in place. The contribution of the skin dose savings to the effective dose saving was relatively low because skin has a tissue weighting factor of only 0.01.

Under the ICRP 103 dosimetry system [23] the "Remainder Tissues" have a tissue weighting factor of 0.12 and are therefore important in the effective dose calculation. Of the remainder tissues located within the abdomen and pelvis, the kidneys, prostate and uterus/cervix were easily identifiable, and the dose changes to these organs were calculated in the same way as for the critical organs. Muscle is distributed throughout the abdomen and pelvis and as such the muscle dose change for each phantom section was calculated as the change in the average dose to the whole section minus the change in the dose to bone within that section. Given the low impact of the muscle dose on the effective dose this was

Table 3. The measured dose savings for each of the 13 organs of interest within the abdomen and pelvis of the RANDO phantom for the scans with lead shielding

Organ/tissue	Tissue weighting factor (ICRP 103)	Dose saving (%)
Bone marrow (red)	0.12	16.6
Bone surface	0.01	9.5
Colon	0.12	33.2
Kidneys	Remainder	3.7
Lymph nodes	Remainder	35.0
Muscle	Remainder	35.0
Ovaries	0.08	24.9
Prostate	Remainder	59.0
Skin surface	0.01	9.3
Small intestine	Remainder	3.8
Testes	0.08	71.7
Urinary bladder	0.04	40.9
Uterus	Remainder	35.4

deemed a reasonable approach. For the same reasons, the dose to the lymph nodes was assumed to be equal to the muscle dose. The change in dose to the remainder tissues was thus calculated as the average dose change across all of the remainder organs within the abdomen and pelvis.

The largest contributor to the effective dose saving was the colon, which has a tissue weighting factor of 0.12 and experienced a dose saving of 33.2% when shielding was used.

For the shielded scans the effective dose was reduced by 4% relative to the unshielded scans. It should be noted that this effective dose saving is achieved over and above dose savings that could be obtained by conventional optimisation strategies such as lowering the tube current, using tube current modulation systems, etc., and is a dose saving that comes with no associated reduction in image quality, because the shielding is placed outside the region being imaged. The 4% reduction in effective dose carries with it an associated 4% reduction in the risk of cancer induction resulting from the CT scan. Given the large number of CT scans that are performed annually and the large contribution to the collective effective dose, use of lead shielding for all CT scans could yield large reductions in the collective effective dose from medical procedures and would also deliver similarly large reductions in collective radiation risk. Berrington de Gonzalez et al [17] estimated that 4100 cancers would result from chest CT scans performed in the United States in 2007. The 4% effective dose saving that was found in this study could have reduced the number of cancer cases from 4100 to 3900.

The results of this study do not allow the authors to make definitive comments on the organ and effective dose savings that could be achieved when lead shielding is used alongside mA modulation techniques, but it is anticipated that the dose savings would be of the same order of magnitude of those found in this study. This should be the subject of further research.

Of the four most radiosensitive organs in the body, only the colon is fully protected by shielding the abdomen and pelvis. Shielding from the shoulders to the dome of the diaphragm for head or abdomen/pelvis scans would fully protect the lungs, stomach and breasts, which are the three other most radiosensitive organs in the body, as well as offering protection to the thyroid and oesophagus. It should therefore also be possible to

achieve significant organ and effective dose savings for head and abdomen/pelvis scans.

Recommendations

These results have shown that significant reductions in both organ and effective dose can be achieved through the use of out-of-plane lead shielding while these dose savings come with no associated effect on image quality. Furthermore, the dose savings yielded by a new shield were shown to be equivalent to those provided by conventional lead aprons while the design of the new shield results in less weight being placed on the anterior side of the patient having the CT scan; this is especially important for paediatric patients and pregnant women. Given the direct relationship between effective dose and the risk of inducing cancer it is recommended that lead shielding should be used on all patients undergoing CT scans regardless of age, gender or body habitus. There will, however, be some situations in which it will not be possible to use such a shielding product, for example in polytrauma imaging where top to toe images of the patient may be acquired in one volume scan. A similar situation may arise when the findings of the initial scan (e.g. chest scan) may require additional images outside the initial scan volume (e.g. scanning into the liver). Users should also take care when positioning lead shielding to ensure that the lead does not extend into the scanned volume and should take particular caution when overscanning or mA modulation are used.

Based on the results of this study it is recommended that lead shielding should be used in conjunction with conventional optimisation strategies in order to deliver patient doses that are considered to be ALARP.

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Conflict of interest

The authors would like to declare a financial interest. This study forms part of a larger research project into the use of lead shielding on pregnant patients undergoing CT scans. As part of the project the authors have designed and developed a new shielding device, which has been licensed to a UK company for manufacture and distribution (ShieldAll™, Rothbond Ltd, Rothbond Ltd, Rossendale, UK).

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