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Computed tomography of the head: An experimental study to investigate the effectiveness of lead shielding during three scanning protocols

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Abstract Purpose The purpose of this experimental study, carried out in 2002, was to investigate the effectiveness of lead shielding during three scanning protocols for Computed Tomography (CT) head examinations.

During CT, the thyroid is irradiated via scattered radiation outside the primary beam. Scientists have proved a definite link between thyroid cancer and radiation but have struggled to quantify the risks from low doses such as those in medical exposures. Children are known to be at higher risks from the effects of radiation than adults.

Method An anthropomorphic phantom was used to simulate the patient. Shielding in the form of a standard lead thyroid shield was used due to the nature of the rotating X-ray beam involved with CT. Thermoluminescent detector chips were used to measure the approximate dose to the thyroid with and without the application of the shield.

Results The effectiveness of shielding varied with scanning technique, as did the thyroid dose due to scattered radiation. The lead shield significantly reduced the dose to the thyroid by 46–58% at the surface of the thyroid and by 37–44% within the thyroid tissue at 1 cm depth.

Conclusion In light of the increasing number of CT scanners, and the fact that head scans account for 50% of all CT examinations and 25% of the collective dose from CT to the UK population, it is important that all methods of dose reduction are

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considered. The use of shielding is a simple yet effective method of dose optimisation that has not been extensively investigated.

Introduction

In 1989 the National Radiological Protection Board (NRPB) conducted a UK survey involving 80% of the CT scanners in service. The results demonstrated an increase in population radiation dose as a result of CT over a 20-year period. It was determined that CT examinations provided approximately 20% of the annual collective dose of about 20,000 manSv from all medical and dental X-rays.[1] This represented a ninefold increase since 1983.[2] The study proved that CT was the largest source of exposure from diagnostic X-rays to the UK population.

In 1998, Shrimpton and Edyvean[3] estimated that with the number of CT scanners in the UK rising from 200 to 370 since the NRPB survey, and taking into consideration increased scanner workload, CT may now contribute 40% of the total annual collective dose to the UK population (from medical radiation exposures) whilst representing only 4% of the total number of examinations

As a result of the NRPB survey[1] 17 general recommendations were made to ensure better control of patient dose from CT by promoting a more systematic approach to the justification and optimisation of exposures.[4] Guidance on clinical practice, equipment and staff training were included, however, the report did not include the use of shielding.

The rise in the number of CT scanners and the increasing importance of trying to reduce the high contribution to the population dose has been the subject of many articles during the 1990s. In 1992 the average effective dose equivalent per CT examination was 5.3 mSv[5] and more recently, Golding and Shrimpton[6] suggest that this figure has risen. This rise could be attributed to changes in CT practice.[7,8] Surveys have demonstrated that patients receive different doses for the same examination; due to the array of different scanner types in use, and also due to operator dependant factors such as techniques and exposure settings on the same scanners.[9–13]

CT head scans are one of the most frequently requested examinations. Early studies concluded that head scans accounted for 50% of all CT scans and 25% of the collective radiation dose from CT.[1]

Dose reduction has been achieved by improvements in scanner design, Quality Assurance (QA) techniques and patient dosimetry (i.e. development of reference levels). Yet it is surprising that with the current emphasis upon dose reduction techniques in CT, the possibility of shielding radiosensitive organs from scattered radiation has not been extensively investigated. Regardless of all the current dose reduction techniques, scattered radiation results in organs outside the primary beam being irradiated.

The benefit of shielding to radiosensitive organs has been acknowledged,[14] yet relatively few studies on the benefits of shielding during CT examinations have been published. Hopper et al.[15] reported a 60% dose reduction during preliminary tests upon shielding the thyroid during C-spine examinations. A study by Price et al.[16] investigated the effectiveness of shielding the male gonads during pelvic CT and reported a 77–93% dose reduction. Hein et al.'s[17] use of a bismuth/latex shield was reported to reduce skin radiation by 40% during CT scanning of paranasal sinuses. More recently, McLaughlin and Mooney's[18] results demonstrate that the use of shielding significantly reduces the dose to the thyroid during CT scanning of the chest, whilst Brnic et al.,[19] Iida et al.[20] and Fujibuchi et al.[21] also acknowledge the use of shielding.

In 1998, a study that addressed the possibility of shielding the thyroid during CT failed to convince scientific bodies into recommending this method of dose reduction.[22] A particular shortcoming to this study was that it failed to address the issue of patients receiving different doses, for the same examination due to the array of scanner types, and due to different techniques and exposure settings on the same scanner.

Although Shah et al.[23] currently recommend that further studies should measure radiation doses from different scanners, there have previously been many studies investigating the dose variation received by patients during head CT. A United States National Survey into the radiation doses associated with standard head CT in adults including 252 scanners, reported dose variations varying by a factor of 2 or more for identical CT scanners.[10] These differences were reportedly due to difference in technique selection, or alternatively from differences in system performance and calibration. Similarly, a study in New Zealand reported variation in doses from routine head scans due to both technical differences between scanners and also variation in clinical techniques.[11] A nationwide survey in Australia reported a variation in dose owing to choice of scan parameters including baseline, slice thickness and spacing, and current time product.[12] In 1998, Smith et al.[13] reported that the variation in absorbed dose in head CT scans is dependant on the combination of both operator dependant and equipment related variables.

Spiral CT techniques enable the radiologist to increase image quality by reducing artifacts in the posterior fossa. Spiral techniques can also be used to reduce acquisition times whilst scanning seriously ill patients or paediatric patients prone to movement. Little has been published with regards to patient dose during spiral CT.[24] In 2001, Hidajat et al.[25] investigated the radiation dose for conventional and spiral CT during different CT examinations at different hospitals. Unfortunately, because only 1 of the 26 hospitals included in the study used a protocol incorporating the spiral technique, statistical comparisons could not be made.

The potential dose reduction achieved by wearing a thyroid shield during CT head scans has not been extensively investigated. Beaconsfield et al.[22] only used a sequential scanning technique. No research has been conducted as to the effectiveness of lead shielding using different scanning protocols and with the newer techniques possible with spiral scanners. This project endeavours to extend the research conducted by Beaconsfield et al. to include three scanning protocols of the head.

Aim of the study

To investigate the effectiveness of lead shielding at reducing dose to the thyroid during three scanning protocols for CT examinations of the head.

Objectives

For three clinically relevant scanning protocols and using an anthropomorphic head phantom:

(1) To measure the dose to the skin overlying the thyroid gland and hence to estimate the dose to the surface of the thyroid due to scattered radiation.
(2) To measure the glandular dose at 1 cm depth within the tissue due to scattered radiation
(3) To estimate the dose reduction achieved at the surface and 1 cm within the thyroid gland using a circumferential lead shield.

Method and materials

An experimental study design was used in order to investigate the effectiveness of lead shielding. As radiation in CT is multi-directional, a standard circumferential thyroid shield was used to protect the thyroid. The experimental condition was the dose to the thyroid when lead shielding was applied to the subject (shielded dose). The control condition was the thyroid dose measured with no lead shielding applied to the subject (unshielded dose). The two conditions were compared to find out if there was a significant difference between them i.e. that there was a significant dose reduction, using a statistical *t*-test. This was conducted for the three different scanning techniques.

A same-subject design was used as according to Hicks,[26(p67)] ''the advantage of this design is that it eliminates the distorting effects of individual subject differences''. The radiation dose was measured on an anthropomorphic phantom both with and without the lead thyroid shield (i.e. in both conditions), the phantom standardising the patient build. As a result patient-to-patient variability was eliminated. All measurements were conducted on the same scanner, a Siemens SOMATOM Plus 4.

The anthropomorphic head phantom

The phantom (Rando; Alderson Research Laboratory, Stamford, Connecticut, USA) was designed such that radiation absorption was similar to that in real patients. It contained a human skeleton adjusted within a mould to normal relations with body contours.

The phantom material had a density of 0.985 g/cm^3 and an effective atomic number of 7.3, identical to those of various human tissues and contents i.e. muscle, fat, lung, bone, air. Subsequently, the phantom would absorb radiation in a manner similar to the human body.

The phantom was sectioned transversely (each section of the head measuring 2.5 cm) making it possible to insert dosimetry systems such as TLDs, photographic film and ionisation chambers (Fig. 1).

For the purpose of this experiment (i.e. CT head examinations), only the top 13 slices were necessary, a clamping device and adhesive tape were

Figure 1 The anthropomorphic head phantom.

used in order to hold all the slabs firmly together and minimise the air gaps between slices as much as possible (Fig. 2). A square radiolucent pad (25 cm, 30 cm, 15 cm) with a concave indentation on the upper surface was used to support the head.

To avoid constant errors, patient position, gantry angle table height and volume of head irradiated were all controlled.

Radiation dose measuring device

Radiation dose to the thyroid was recorded using TLD-100H High Sensitivity Lithium Fluoride (LiF) chips, which were able to detect a wide range of doses from 1 μGy to 10 Gy. Being small (1/8, 1/8, 0.6 mm), they were approximately 15 times more sensitive than standard LiF chips making them ideal to detect the low energy radiation involved during this study. Subsequently, it was only necessary to irradiate the head phantom once in order to obtain a measurement instead of several times as in other experiments, for instance, Price et al.[16]

TLDs, enclosed in opaque numbered sachets to exclude dirt and light, were applied to the phantom at marked sites to detect the scattered radiation. Five TLDs were also used to measure the mean background radiation value which was then subtracted from each dose measurement.

Figure 2 Positioning arrangement of the phantom.

Scanning protocols

The protocols used were based on those recommended by the manufacturer of the CT scanner as described by Maatsch and Knapheide.[27] The scanning parameters for each protocol are displayed in Table 1.

This sequential scanning technique consisted of 5 mm contiguous slices through Region 1 (the posterior fossa) followed by 10 mm contiguous slices through Region 2.

The Volume Artifact Reduction (VAR) Technique combines two thin slices to form a single CT image featuring both the low noise characteristics of thick slices and the artifact reduction common to thin slices.[27] The VAR technique can only be utilised with spiral scanners. This scanning technique incorporated a spiral scan through Region 1 using a slice thickness of 2 mm, a pitch of 1.25 and reconstruction interval of 4 mm. This was followed by a sequential scan conducted through Region 2 with 10 mm contiguous slices.

The spiral scanning technique incorporated a spiral technique through Regions 1 and 2 using an 8-mm thick slice and a pitch of 1.5.

Calculations

Mean absorbed dose measurements were calculated from the TLD readings both at the surface and at 1 cm depth, with and without the thyroid shield for each technique. The mean dose reduction for each technique was calculated by subtracting the mean shielded dose from the mean unshielded dose (for both surface and 1 cm depth measurements). The percentage dose reduction was then calculated as follows:

$$D_R\% = \frac{D_U - D_S}{D_U}100$$

where D_R = mean absorbed dose reduction; D_U = mean absorbed dose without shielding; D_S = mean absorbed dose with shielding; and $D_R\%$ = percentage dose reduction.

Table 1 Scanning parameters

	Techniques		
	Sequential	VAR	Spiral
Region 1 (posterior fossa)			
Slice thickness (mm)	5	2	8
Feed/rotation (mm/rot)	—	2.5	12
Rotation time	1.5	1.5	1.0
kV	140	140	120
mA	171	159	170
Direction	Caudo-cranial	Caudo-cranial	Caudo-cranial
Region 2 (the rest of the cranium)			
Slice thickness (mm)	10	10	8
Feed/rotation (mm/rot)	—	—	12
Rotation time	1.5	1.5	1.0
kV	140	140	120
mA	146	146	170
Direction	Caudo-cranial	Caudo-cranial	Caudo-cranial

Therefore, it must be noted that tabulated dose factors are *adjusted*.

Statistical tests

In order to assess whether shielded and unshielded dose measurements were significantly different, the independent *t*-test was performed, a 5% confidence level being considered significant.

TLD measurements

Beaconsfield et al.'s study[22] took one dose measurement at the surface and one at 1 cm depth at a level of C5/6. Hopper et al.[15] placed four TLDs over the thyroid and acknowledged that the spatial distribution of the scattered radiation may differ over the whole organ. During this study, there were a limited number of TLDs available and so a compromise was reached in using two TLDs instead of four in order to obtain a more accurate and realistic dose description.

Initially, two TLDs were placed at identical levels in the approximate position of the left and right lobes both at the surface and at 1 cm depth. A small number of pilot measurements were taken to investigate how dose varied along the transverse plane of the phantom. The preliminary results were indicative that the dose to each lobe would be very similar and representative of the average dose over the whole thyroid. Chopp et al.[28] indicated that dose would vary over the long axis of the patient i.e. the dose falling gradually with increasing distance from the head. Therefore, TLDs were placed in the approximate position of the upper and lower halves of the left lobe of the thyroid.

TLDs were positioned on the surface of the thyroid as follows:

- Upper half of left lobe—at the base of slice 10, 1.5 cm to the left of the median sagittal plane, 2.5 cm below the level of the thyroid eminence (2.5 cm above the lower TLD);
- Lower half of left lobe—at the base of slice 11, 1 cm above the manubrium of the sternum, 1.5 cm to the left of the median saggital plane.

TLDs were also positioned at 1 cm depth within the thyroid tissue:

- Two TLDs were positioned at 1 cm depth adjacent to the superficial TLDs in the region of the left lobe of the thyroid, in between slices 10 and 11 and in between slices 11 and 12.

Experimental procedure

For each of the three scanning techniques:

- Four TLDs were placed at marked sites upon the phantom.
- The phantom was positioned on the scanner table and a topogram was performed.
- A scan was performed using one of three scanning techniques.
- The identification number and position of each TLD were noted before being removed. New unexposed TLDs were then placed in identical positions.

The above steps were repeated three times with shielding and three times without for each technique. Eighteen scans was performed, each scan resulted in four dose measurements. A total of 72 dose measurements were obtained. Five background TLDs remained outside the scanner room at all times. All TLDs were sent to a medical physics laboratory to be read, five background TLDs accompanied each batch. The background dose was automatically subtracted from the TLD measurements shown in the Results.

Results

Effectiveness of lead shielding using sequential, VAR and spiral scanning techniques

The largest unshielded dose measured at the skin surface overlying the thyroid, due to scattered radiation, was measured during head scans using the sequential scanning technique (0.69 mGy). The smallest unshielded thyroid dose measured at the skin surface due to scattered radiation was measured during head scans using the spiral scanning technique (0.21 mGy).

The largest unshielded thyroid dose due to scattered radiation measured at 1 cm depth was measured during head scans using the sequential scanning technique (0.71 mGy).

The smallest unshielded thyroid dose was measured during the spiral scanning technique (0.21 mGy).

t-Tests showed that unshielded and shielded dose values measured at the surface differed significantly with shielded dose measuring significantly lower than unshielded dose. These results suggest that the thyroid shield significantly reduces dose to the skin overlying the thyroid during head scans performed using all three scanning techniques (Table 2). A statistically significant decrease in dose was also seen when measurements were taken at 1 cm depth in tissue.

Table 2 also summarises the results obtained during the scanning techniques. Mean dose measurements were calculated from the raw data to obtain a mean unshielded dose value (D_U) and a mean shielded dose value (D_S) for TLDs placed on the surface of the phantom and at 1 cm depth within the phantom in the approximate position of the left lobe of the thyroid. The mean percentage dose reduction (D_R%) was then calculated.

The results in Table 2 indicate that lead protection is more effective at reducing thyroid dose due to scattered radiation at the surface than at 1 cm depth. Fig. 3 illustrates the percentage dose reduction of the unshielded dose measured at the surface and at 1 cm depth for all three scanning techniques.

It can also be seen from Table 2 that dose measurements at 1 cm depth are higher than the corresponding measurements at the skin surface.

Fig. 3 illustrates that during all techniques the minimum dose reduction at the surface was 46.1% and the maximum was 57.6%. Similarly, the minimum dose reduction at 1 cm depth was 37.1% and the maximum was 43.7%.

Table 2 Mean (±standard deviation, range, *n*) unshielded and shielded thyroid dose, dose reduction and percentage dose reduction at surface and 1 cm depth during the three scanning techniques and statistical comparisons

TLD position	D_U (±SD,range,n)	D_S (±SD,range,n)	D_R	D_R%	t	df	p[a]
Sequential scanning							
Surface	0.69 (±0.04,0.63–0.73,4)	0.29 (±0.09,0.20–0.37,6)	0.39	57.6	−9.64[c]	7.95	0.00
1 cm Depth	0.71 (±0.14,0.58–0.83,4)	0.40 (±0.14,0.26–0.54,6)	0.31	43.7	−3.50[b]	8.00	0.008
VAR technique							
Surface	0.56 (±0.03,0.52–0.60,6)	0.29 (±0.06,0.21–0.35,6)	0.27	48.9	−10.03[c]	8.025	0.00
1 cm Depth	0.60 (±0.10,0.49–0.70,6)	0.36 (±0.11,0.26–0.49,6)	0.23	39.4	−3.958[b]	10.00	0.003
Spiral scanning							
Surface	0.21 (±0.02,0.19–0.23,5)	0.11 (±0.02,0.09–0.15,6)	0.10	46.1	−7.784[b]	9.00	0.00
1 cm Depth	0.23 (±0.06,0.17–0.31,6)	0.15 (±0.04,0.10–0.21,6)	0.09	37.1	−3.169[b]	10.00	0.01

D_U = Mean Unshielded Dose (measured in mGy); D_S = Mean Shielded Dose (measured in mGy); D_R = Mean Dose Reduction (measured in mGy); D_R% = Mean Percentage Dose Reduction; SD = Standard Deviation; n = number of TLD measurements; df = degrees of freedom (NB adjusted dose factors).

[a] Two tailed significance value is presented.

[b] Levene's test for Equality of Variances was *not* significant ($p > 0.05$), therefore results of Equal variance formula reported.

[c] Levene's test for Equality of Variances was significant ($p < 0.05$), therefore results of Unequal variance formula reported.

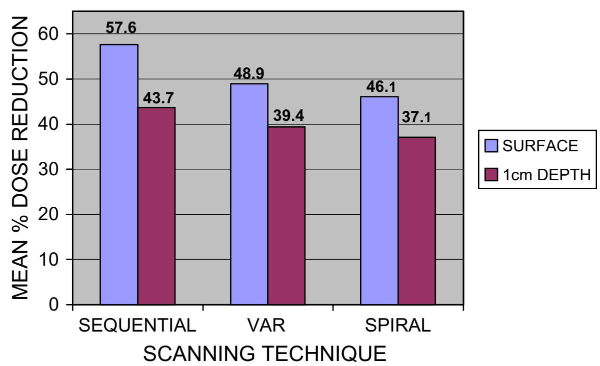

Figure 3 Percentage dose reduction measured at surface and 1 cm depth for each scanning technique.

During head scans conducted with all three techniques, the dose reduction achieved at 1 cm depth was less than at the surface.

Further statistical analysis of TLD dose measurements obtained at surface and 1 cm depth

TLD measurements were taken at four points on the upper and lower halves of the left lobe of the thyroid on phantom slices 10 and 11. *t*-Tests were conducted on all four sets of TLD measurements at each position on the thyroid gland. A *p* value of <0.05 was considered significant. All *t*-tests showed that unshielded and shielded dose measurements differed significantly suggesting that the thyroid shield significantly reduced the dose to the thyroid during all three scanning techniques.

Percentage dose reduction calculated for each scanning technique

The mean unshielded and shielded dose values were used to calculate the percentage dose reduction. Figs. 4—6 express the results in graphical form where:

S10/SURF = TLD positioned on surface of slice 10
S11/SURF = TLD positioned on surface of slice 11
S10/1CM = TLD positioned at 1 cm depth on base of slice 10
S11/1CM = TLD positioned at 1 cm depth on base of slice 11

It is evident from Figs. 4—6 that during all scanning techniques, TLDs positioned on slice 10 of the head phantom yield higher dose measurements (at surface and 1 cm depth) than those positioned on slice 11.
For unshielded dose values:

Measurements on slice 10 indicate that the thyroid dose due to scattered radiation at 1 cm depth is higher than that at the surface.
Measurements on slice 11 indicate that the thyroid dose at 1 cm depth due to scattered radiation is less than that at the surface.

For surface measurements:

During the sequential, VAR and spiral scanning techniques, the percentage dose reduction achieved at slice 11 was greater than that at slice 10.

For 1 cm depth measurements:

During the sequential and VAR scanning techniques, the percentage dose reduction at slice 11 was greater than that at slice 10.
During the spiral scanning technique, the percentage dose reduction at slices 10 and 11 was very similar.

Anomalous results

Four TLD measurements were eliminated from the study during the sequential scan technique. Evidently, these measurements differed in that they were consistently lower than all other measurements for that scan technique. In fact, the results were very similar to values obtained during the

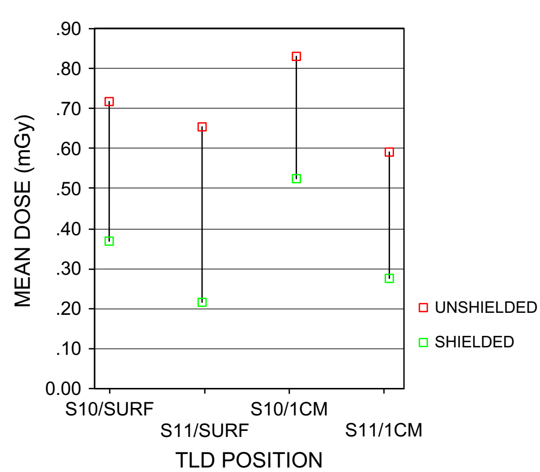

Figure 4 Mean unshielded and shielded thyroid dose measured at each TLD position during sequential scanning technique.

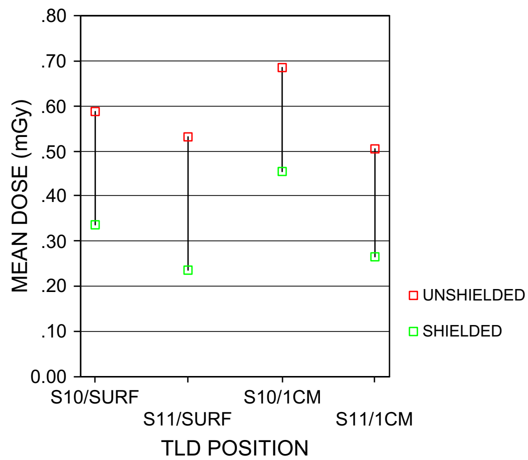

Figure 5 Mean unshielded and shielded thyroid dose measured at each TLD position during VAR scanning technique.

VAR technique. It is possible that manual error resulted in the VAR scanning technique being conducted instead of the sequential scanning technique whilst these four TLDs were in position. Other possibilities include: the operator incorrectly selecting any one of the scanning parameters, or segments of the phantom not being positioned in line with the others. There is a possibility that these dose measurements were not anomalous. The performance of the scanner may have varied, its output (number of X-ray photons) changing considerably during the three head scans, resulting in a wider range of scattered radiation measurements. The dose measurements obtained therefore, might not be representative of the typical performance of the CT scanner i.e. the amount of scatter may have differed if more scans were taken. Unfortunately, the number of measurements

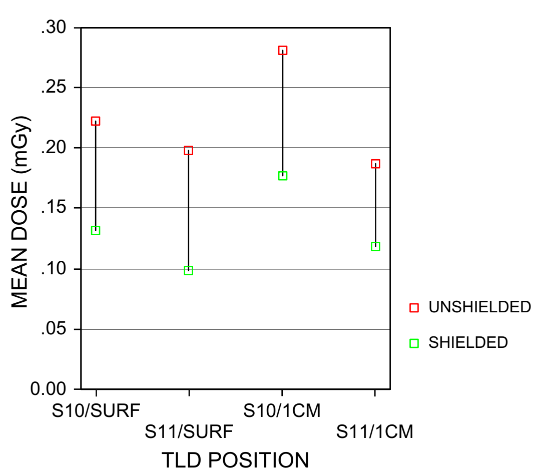

Figure 6 Mean unshielded and shielded thyroid dose measured at each TLD position during spiral scanning technique.

taken during this experimental study was governed by both scanner access and TLD constraints (this included cost of TLDs and time taken to process them). Subsequently, this resulted in mean dose measurement being calculated from TLD measurements made during two scans. The reliability of the results could have been improved if more scans had been conducted. A repeat study would incorporate Quality Assurance (QA) techniques to reduce the likelihood of inconsistencies.

Discussion

Thyroid dose due to scattered radiation

Emphasis has been placed on the optimisation of dose through the appropriate choice of exposure settings and scan volume, improvements in scanner design and QA techniques.[29] This study and others[16,19] provide evidence that minimising patient dose due to scattered radiation by shielding can further reduce dose to radiosensitive organs outside the primary beam without affecting the image quality. The results of this study support the findings of Beaconsfield et al.[22] in that a definite dose reduction at the thyroid gland due to scattered radiation was achieved during all three techniques.

Unshielded radiation doses measured at the surface and at 1 cm depth were different for each protocol indicating that the amount of scattered radiation arising from each head scan varied with examination technique. The results of this study were therefore consistent with those of Shrimpton et al.,[1] Conway et al.,[10] Poletti,[11] Smith and Shah[12] and Smith et al.[13]

This study has shown that in addition to all other current optimisation methods, lead shielding would also be a plausible dose reduction technique. The results indicated that during all three scanning protocols, the lead shield significantly reduced the amount of scattered radiation irradiating the thyroid.

The amount of scattered radiation detected at the thyroid varied with each head scan technique. Results indicated that most scatter was generated during the sequential scanning technique, followed by the VAR technique and finally the least with the spiral technique. In retrospect, a repeat study would exclude the spiral technique since in practice it is not used for standard head scans due to problems with image reconstruction when the gantry is angled. This study demonstrates that in comparison to the sequential technique, the spiral technique can result in lower patient doses due to scattered radiation. There is a lack of published data comparing patient dose resulting from sequential, VAR and spiral scanning techniques.

Phantom measurements upon the thyroid indicated that head scans using the sequential technique resulted in a mean absorbed dose of 0.69 mGy at the surface and 0.71 mGy at 1 cm depth. The VAR technique resulted in a mean absorbed dose of 0.56 mGy at the surface and 0.6 mGy at 1 cm depth. Upon application of the thyroid shield, mean absorbed dose at the surface was 0.29 mGy during both techniques and 0.4 mGy and 0.36 mGy at 1 cm depth for the sequential and VAR techniques, respectively. The implications of this are:

- Patients undergoing a head scan with either technique will benefit significantly through wearing a thyroid shield;
- The variety in patient dose due to technique is greatly reduced through wearing a thyroid shield

The effectiveness of lead shielding varied with scan technique. The greatest dose reduction was achieved during the sequential scanning technique (58%—surface, 44%—1 cm depth) followed by the VAR technique (50%—surface, 39%—1 cm depth). The smallest dose reduction was achieved during the spiral scan technique (46%—surface, 37%—1 cm depth).

Conclusion

Specialists are working hard to try and minimize the doses associated with CT examinations and to try and reduce the variation of doses received by patients. A partial solution to both of these problems would be to give patients lead protection.

Thyroid shielding would be especially beneficial to patients who receive larger doses whilst undergoing many CT examinations due to long-term illness or injury. This study has proved that for three scanning techniques, shielding the radiosensitive thyroid will significantly reduce the dose from scattered radiation. As a consequence, the risks of developing cancer will also be reduced.

Although the risks are difficult to quantify, Picano[30] stresses that any radiation may be detrimental to the health of the patient, and Picano,[30] Brenner et al.,[31] Golding and Shrimpton[6] and Frush et al.[32] advise that we all become more aware of the long term risks of exposure to radiation. Perhaps Beaconsfield's advice now needs to become practice:

''*We feel strongly that it is time to include the simple precaution of 'tucking' patients in with a collar and bib, particularly those in the paediatric and young age groups*'' (Beaconsfield et al.[22(p666)]).

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