RESEARCH ARTICLE

Effectiveness of thyroid gland shielding in dental CBCT using a paediatric anthropomorphic phantom

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Objectives: The purpose of the study is to evaluate the effectiveness of thyroid shielding in dental CBCT examinations using a paediatric anthropomorphic phantom.

Methods: An ATOM[®] 706-C anthropomorphic phantom (Computerized Imaging Reference Systems Inc., Norfolk, VA) representing a 10-year-old child was loaded with six thermoluminescent dosimeters positioned at the level of the thyroid gland. Absorbed doses to the thyroid were measured for five commercially available thyroid shields using a large field of view (FOV).

Results: A statistically significant thyroid gland dose reduction was found using thyroid shielding for paediatric CBCT examinations for a large FOV. In addition, a statistically significant difference in thyroid gland doses was found depending on the position of the thyroid gland. There was little difference in the effectiveness of thyroid shielding when using a lead vs a lead-equivalent thyroid shield. Similar dose reduction was found using 0.25- and 0.50-mm lead-equivalent thyroid shields.

Conclusions: Thyroid shields are to be recommended when undertaking large FOV CBCT examinations on young patients.

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Introduction

In recent years, CBCT has become an established modality in dentomaxillofacial imaging. However, CBCT imaging is associated with a higher radiation-induced cancer risk than conventional dental radiography. Several studies^{1–8} have measured the organ and effective doses for a range of clinical protocols and dental CBCT machines. However, only three studies^{9–11} have investigated the organ doses to young children using paediatric

anthropomorphic phantoms. Since the majority of dental CBCT machines are not optimized for paediatric patients and do not offer paediatric-specific imaging protocols, the thyroid gland doses to young children are generally found to be higher than those of adolescent or adult patients owing to their smaller size.

The thyroid gland is one of the most radiosensitive organs in the head and neck region.¹² Assuming careful patient positioning during CBCT examination, the thyroid gland should be exposed to scatter radiation only. Therefore, the absorbed dose to the thyroid gland is small compared with other radiosensitive organs that are exposed to primary beam, *i.e.* salivary glands or brain. However, the contribution of the thyroid gland dose to the effective dose can be significant owing to its high radiosensitivity.^{5,11}

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Al Najjar *et al*⁹ found using a 5-year-old phantom doses to the thyroid gland in the range of 0.16–0.80 mGy when using the i-CAT® (Imaging Sciences, Hatfield, PA) and Iluma® (3M IMTEC Corporation, Ardmore, OK) CBCT units. These doses to the thyroid gland are significantly higher than that found in an adult phantom study. Theodorakou *et al*¹¹ reported thyroid organ doses in the range of 0.04–1.33 mGy for a range of CBCT machines and imaging protocols using a 10-year-old phantom. Ludlow and Walker¹⁰ measured thyroid doses between 0.02 and 1 mGy using a 10-year-old phantom and the i-CAT FLX (Imaging Sciences). The studies previously mentioned also demonstrate there was a difference in the absorbed radiation dose to the thyroid gland in a paediatric phantom when using differing fields of view (FOVs) and exposure parameters.

The UK National Radiation Protection Board¹³ in 2001 suggested thyroid shields should be used in dental radiography for those few cases where the thyroid gland may be in the primary beam, based on the advice from a medical physics expert. The National Radiation Protection Board suggested a thickness of lead equivalence of ≥ 0.25 mm for lead aprons, for an adult providing patient assistance. However, no such recommendation was made for thyroid shields, and there are no international recommendations for the use of thyroid shielding in CBCT. In Europe, the use of thyroid shielding should be made locally with the assistance of a medical physics expert.¹⁴ In the UK, the use of thyroid shielding has been recommended depending on the CBCT machine and imaging protocol.¹⁵ However, in the USA, thyroid shielding is being recommended whenever possible¹⁶ or routinely.¹⁷

To the authors' best knowledge, there are no published studies evaluating the effectiveness of shielding the thyroid gland for paediatric patients during CBCT examination. Furthermore, there are a wide variety of designs, materials and thicknesses of thyroid shields available with limited information on their clinical usefulness.

The aim of the study was to assess the effectiveness of thyroid shields on dose reduction to the thyroid gland using a 10-year-old anthropomorphic phantom.

Methods and materials

Anthropomorphic phantom

The head, neck and shoulder sections of a paediatric tissue-equivalent anthropomorphic phantom (ATOM® Model 706-C; Computerized Imaging Reference Systems Inc., Norfolk, VA) representing a 10-year-old child was used in this study (Figure 1). This phantom was constructed of 25-mm thick slices, containing tissue-equivalent materials constructed of epoxy resins. All the bones within the phantoms were homogeneous, and the composition was formulated to represent the appropriate age and average bone density of a 10-year-old child. The phantom

Figure 1 Paediatric tissue-equivalent anthropomorphic phantom of the head, neck and shoulders (ATOM® Model 706-C; Computerized Imaging Reference Systems Inc., Norfolk, VA) representing a 10-year-old child.

contained pre-drilled holes for the placement of dose-meters in a 1.5×1.5 -cm grid pattern, allowing the position of an organ of interest to be determined. For the grid pattern, all the pre-drilled holes were filled with 5-mm diameter $\times$ 25-mm long solid plugs of tissue-equivalent material. The plugs were modified to allow the placement of thermoluminescent dosimeters (TLDs) at either the top or bottom layer of the 25-mm slice.

Location of thyroid gland

No paediatric imaging textbook could be found to locate the thyroid gland in a 10-year-old patient to facilitate the positioning of the thyroid gland within the anthropomorphic phantom. Ludlow and Walker¹⁰ suggested locating the organs of interest using individual expertise. At the commencement of the study, no information on the placement of dosimeters for the thyroid gland could be identified. Hence, a preliminary study was performed to determine the position, level in the phantom and relationship of the thyroid gland using the cervical vertebrae as an anatomical reference.

A review of the Radiology Information System (CRIS Healthcare Software Solutions, Mansfield, UK) of the Hospital was performed to identify all CT and MR examinations of the neck and cervical vertebrae of

10-year-old patients over a 4-year period (October 2007 to September 2011). This identified 21 cases that were reviewed to determine if a complete image of a normal thyroid gland and cervical vertebrae was contained within the data set. The exclusion criteria included an incomplete image of the thyroid gland and abnormal anatomy or pathology affecting the thyroid. Ten data-sets were appropriate for inclusion. The average height of the thyroid gland measured in the sagittal images was 44.6 mm with a standard deviation of 4.2 mm. The relationship of the thyroid gland to the cervical spine demonstrated that the upper limit of the gland corresponded to the level of C4/C5, and the lower extent of the gland corresponded to the middle of C7.

A single examiner (specialist in dental and maxillofacial radiology) evaluated the ten data sets using Centricity 3.0 software (Centricity Radiology RA1000; GE Healthcare, Fairfield, CT) using Barco diagnostic monitors (Barco Ltd, London, UK). This process was repeated on two separate occasions to identify the thyroid gland in relation to the cervical vertebrae in the axial and sagittal planes of the neck in a 10-year-old patient from the skin surface. This enabled the position of the thyroid gland in the anthropomorphic phantom to be determined.

Absorbed dose measurements

Absorbed dose measurements were performed using TLDs: TLD-100H (LiF; Mg, Cu, P) (Harshaw Thermo Fisher Scientific Inc., Waltham, MA). All TLDs were calibrated in air against a 6-cm³ ionization chamber (Radcal 9010; Radcal Corporation, Monrovia, CA) coupled with an electrometer with calibration traceable to national standards (National Physical Laboratory, Teddington, UK). A conventional diagnostic X-ray tube at 80 kV (half-value layer = 3.02 mm aluminium) was used. The coefficient of variation for the energy response was <5% for the TLDs used in this study.

The TLDs were annealed at 240 °C for 10 min and rapidly cooled to ambient temperature to eliminate any residual signal. Once irradiated, the TLDs were read in an automatic reader (Harshaw 5500; Harshaw Thermo Fisher Scientific Inc.) as per the protocol described by Theodorakou *et al.*¹¹

Location of thermoluminescent dosimeter in the phantom

From the review of 10-year-old patients' CT and MR scans, the position and depth of the thyroid gland was determined to be within the most superior aspect of Slice 9 and Slice 10 of the phantom. Therefore, four single TLDs were placed in Slice 9 and two TLDs in Slice 10 of the phantom at the superior aspect of the slice level (Figure 2). In total, six TLDs were placed into the phantom at the pre-determined level of the thyroid gland.

Thyroid shields

Five thyroid shields of three different designs made of either lead or lead-equivalent material were evaluated in the study. The inclusion criteria were that these thyroid shields were selected owing to the availability within the

UK. Thyroid shields 1 and 2a contained 0.25-mm lead and thyroid shields 2b and 2c contained bismuth with a lead equivalence of 0.25 mm and 0.50 mm, respectively (Rothband & Co. Ltd, Rossendale, UK). The fifth lead-equivalent thyroid shield contained barium sulphate, manufactured by Gray Shield (Rothband & Co. Ltd) with a lead equivalence of 0.125 mm. Figure 3 shows the three designs and lists the lead and lead-equivalent thicknesses per thyroid shield.

CBCT machine and exposure parameters

The 3D Accuitomo F170 CBCT scanner (J. Morita, Kyoto, Japan) was used in the study. The largest FOV, 17-cm diameter by 12-cm height was utilized to maximize the irradiated volume and scatter radiation. The manufacturer's recommended exposure parameters of 90 kV, 5 mA and 17.5-s exposure time were used with a full-beam rotation.

The region of interest selected for the CBCT scan was the facial skeleton, including the soft-tissue profile, as potentially used in an orthodontic examination. Figure 4 shows the posterior–anterior and lateral scout views of the phantom.

Experimental set-up

The anthropomorphic phantom was positioned similar to a 10-year-old patient using an adjustable tripod and metal tray to stabilize the base of the phantom. The correct positioning of the facial skeleton and region of interest was achieved using laser beam markers and lateral and posterior–anterior scout views. Once the optimal position of the phantom had been established, the lowest slice was secured to the metal tray to avoid movement of the phantom during the CBCT exposure and enabling reproducible positioning of the phantom.

The phantom was irradiated five times without a thyroid shield using five different sets of TLDs to assess repeatability. Then, the thyroid shield was placed around the phantom as per the manufacturer's recommendation and exposed five times using five different sets of TLDs. This was repeated for the five thyroid shields resulting in six experimental scenarios, including the thyroid shield-free exposure.

To assess the variability between the two slices representing the position of the thyroid gland, the average dose and standard deviation of the five repeated exposures were calculated for each slice and experimental scenario. In addition, the average dose for all TLD locations was calculated to estimate the dose to the whole of the thyroid gland for each scenario.

The coefficient of variation was used to determine the consistency of the measured dose for each of the six TLD locations. For each well in the phantom, the coefficient of variation was calculated from the five repeated measurements.

Statistical analysis was undertaken using IBM SPSS® Statistics v. 20.0 (IBM Corp, Armonk, NY) to determine interslice and interscenario differences.

Figure 2 Sites selected for the location of the thermoluminescent dosimeters.

Results

The average coefficient of variation of all TLDs used in the present study was 8%, which is consistent with tolerances used in similar CBCT dosimetry studies.⁴ However, of the 180 individual TLD measurements obtained, one was reported to be an outlier, with a value outside the 95% confidence interval. Therefore, this measurement was excluded from the analysis.

The average doses and standard deviations are shown in Table 1 for each slice individually and as the average of both slices, representing the thyroid gland dose.

Statistically significant interslice differences in all six scenarios and all shield scenarios were found ($p < 0.001$). For the average thyroid gland dose, statistically significant differences were found between the thyroid shield-free and the thyroid shield scenarios ($p < 0.001$). No differences were found between thyroid shield Design 1 and 2

($p = 0.116$ – 1.000). Thyroid shield Design 3 showed a significantly lower dose reduction than did the other shield scenarios ($p < 0.001$) (Figure 5).

A statistically significant difference was found between the thyroid shield-free and use of the thyroid shield scenarios for the superior slice ($p < 0.001$). No statistically significant differences were found between thyroid shield Designs 2a, 2b and 2c ($p = 1.000$) and between Designs 1, 2a and 2b ($p = 0.058$ – 0.061). Design 3 showed a statistically significant difference to the thyroid shield-free scenario ($p < 0.001$) and the other thyroid shields ($p < 0.001$). However, the dose reduction using thyroid shield Design 3 was smaller than were the other thyroid shields. Thyroid shield Designs 1 and 2 showed statistically significant differences compared with the thyroid shield-free scenario ($p < 0.001$) for the inferior slice. However, no statistically significant differences were found between Designs 1 and 2 ($p = 0.056$ – 1.000). No statistically significant difference was found between the thyroid shield-free and Design 3 ($p = 0.121$). The percentage dose reduction achieved by the five thyroid shield scenarios, compared with the thyroid shield-free scenario is shown in Table 2.

When the whole of the thyroid gland is considered, thyroid shield Design 2 performed best regardless of its material and thickness. However, when evaluating each slice separately, Design 1 had a better performance than the other shields at the inferior slice. A lower dose reduction was seen with Design 3 for the superior and inferior slices and for the thyroid gland as a whole. Statistically significant differences were found between the superior and inferior slices for all six scenarios. All thyroid shields of Design 2 performed similarly, regardless of whether the shield contained lead or an equivalent material, and the thickness of the shielding material had no significant effect.

Figure 3 The three designs of thyroid shield used in this study. Rothband™ and Gray Shield™ are manufactured by Rothband & Co. Ltd, Rossendale, UK. *equates to a lead-equivalent material in the thyroid shield. Pb, lead; Pb eq, lead equivalent.

Discussion

The results of this study should be cautiously translated to the clinical situation, as this is a laboratory-based

Figure 4 Scout image of the CBCT volume captured using the Morita Accuitomo F170 (J. Morita, Kyoto, Japan).

research study. To the authors' knowledge, this is the first study testing the effectiveness of a range of thyroid shields using a 10-year-old child phantom in CBCT imaging.

Position and shape of the thyroid

The location of the thyroid gland in children and in anthropomorphic phantoms is considered of critical importance. Studies performed to date have used adult phantoms where the position of the thyroid gland is well known. Several dosimetric studies^{1,7,18,19} used the positioning of TLDs in the head and neck region of an adult phantom described in the Ludlow *et al*⁴ study.

The position and shape of the thyroid gland in a paediatric phantom was determined by analysis of patients' images. Transferring the true anatomical position of the thyroid gland to the dosimetric phantom was not a simple process, however, the current approach could be considered as the best estimate. This was owing to the limited number of patients imaged using CT and MR and the relatively small sample size of only ten patients to be included in the analysis. Other known factors that influence the dimension of the thyroid gland include gender, growth and advanced developmental age,²⁰ which were not considered in the current study.

Position of the thermoluminescent dosimeters

The use of TLDs in dosimetry phantoms is a common methodology used in dose studies. However, there is a lack of consensus regarding the position and number of TLDs in a phantom,⁵ and variations were recorded even when the same phantom was used.^{21–23} A wide range of TLDs has been used to record the dose to the thyroid gland, ranging from one to seven TLDs.^{3,11} There is a general agreement that the use of several TLDs for each organ allows for a more accurate average organ dose to be calculated. As the present study focused on thyroid gland dose, the use of six TLDs in the thyroid region was considered most practicable.

The published paediatric dose studies have used the same brand of dosimetry phantom. One study used TLDs,¹¹ while the other studies used optically stimulated luminescent dosimeters.^{9,10} In all these studies, the

location of the dosimeters in the phantom was determined by expert opinion.

This study demonstrated most of the thyroid gland was located in the superior slice (Slice 9). However, owing to limitations in the anthropomorphic phantom design, the thyroid gland had to be contained in one slice of 2.5-cm height. An adequate number of TLDs were positioned across the horizontal plane of the two slices.

The Ludlow and Walker¹⁰ study used two slices and three dosimeters to represent the thyroid gland at the same vertical position in the ATOM 706 phantom. Ludlow and Walker¹⁰ placed a single dosimeter at the top of Slice 8 to represent the superior pole of the gland, and two dosimeters at Slice 9 for the main body of the thyroid gland. The present study found that the thyroid gland is located in a more superior position than in an adult, and the top of the thyroid gland would be at the level of the chin in a child.

Positioning of the patients in the longitudinal axis has been shown to be critical, mainly in the transition between the floor of mouth and the thyroid. Variations of up to 15% in dose to the thyroid gland have been seen with slight changes in patient positioning.²⁴ Ludlow and Walker¹⁰ reported slight changes in the position of the dosimeters when positioned at the edge of the X-ray beam can also alter the dose significantly.

Therefore, it is important to ensure that the thyroid shield is placed sufficiently high on the neck with good adjustment.^{18,19} A simple strategy when positioning the patient during CBCT examination is to tilt the mandible upwards extending the neck, so the exposure to the thyroid gland is reduced by the increased distance of the beam and the gland. This strategy has been proved to be effective in dental CBCT and medical CT.^{3,25} However, such a manoeuvre is not possible in a laboratory study using rigid anthropomorphic phantoms.

Exposure parameters

The largest FOV is not routinely used on paediatric patients. However, it was chosen for the purposes of this study, using 17×12 cm and the exposure parameters of 90 kV, 5 mA and 17.5 s to maximize the scattered

Table 1 Average doses (mGy) and standard deviations for all scenarios

Thyroid gland level studied	Average doses (mGy); standard deviations					
	No thyroid shield	Design 1	Design 2a	Design 2b	Design 2c	Design 3
Superior slice	2.57; 0.16	1.69; 0.08	1.46; 0.03	1.46; 0.07	1.38; 0.19	2.06; 0.05
Inferior slice	0.68; 0.06	0.42; 0.03	0.45; 0.03	0.50; 0.04	0.49; 0.02	0.61 ^a ; 0.05
Whole thyroid gland (superior + inferior slice)	1.62; 1.0	1.05; 0.67	0.95; 0.53	0.98; 0.51	0.94; 0.48	1.34; 0.77

^aNo statistically significant difference to the thyroid shield-free scenario.

radiation. According to the European guidelines, the largest FOV should not be routinely used. However, the largest FOV may be justified for cases involving combined orthodontic/surgical intervention, which would not normally include a 10-year-old child.

Thyroid shielding results

Most studies focus on a single phantom slice when studying the thyroid gland.^{3–5,7} This study showed a statistically significant difference between the two slices. This demonstrates the importance of measuring the dose at differing heights to obtain more accurate dose measurements.

The results of the thyroid shielding all exceed the 10% of patient dose reduction suggested for clinical impact.²⁶ Direct comparison with other studies was not possible as this was the first study evaluating the effectiveness of thyroid shields in a child model. Adult dosimetry laboratory studies have shown a dose reduction ranging from 44% to 72%.^{18,19,27}

The average thyroid dose can be compared with the study by Theodorakou *et al*,¹¹ since a similar phantom, same machine, exposure factors and FOV were used. The average thyroid dose obtained without a thyroid shield was higher than that recorded by Theodorakou *et al*.¹¹ This difference may be explained by the different

location of the TLDs. Theodorakou *et al*¹¹ positioned the TLDs at the bottom of Slice 9 and top of Slice 10. Comparing the results for Slice 10, similar TLD doses were obtained between the two studies.

For thyroid shield Design 1, a high positioning was attempted to best protect the thyroid gland. However, this position seems not to be easily achievable in clinical practice. The shield design was difficult to maintain beneath the chin as required for thyroid protection in children, as there was no band to secure the shield behind the neck. It would appear that the shield is designed to rest on the patients' shoulders. This thyroid shield did perform better when shielding the most inferior slice representing the thyroid gland, most likely owing to its greatest inferior extension. The lateral lead coverage securing the shield around the neck was displaced inferiorly when positioning the shield potentially leaving the thyroid gland exposed to radiation. This may account for the poorer behaviour, although this was statistically not significant.

Thyroid shield Design 2 in its three different variations had the same performance regardless of the thickness (0.25 or 0.50 mm) of the shielding material (lead and bismuth). Therefore, it is possible to infer that 0.25 mm of lead or lead-equivalent material is sufficient to reach a good level of thyroid protection, and the 0.50-mm lead has no further effect. Lead-equivalent shields are recommended as a lighter alternative to those containing lead, however, differences in weight are less important when using thyroid shields. Therefore, lead-equivalent and lead thyroid shields are as effective as each other in CBCT imaging. Studies in adult phantoms have shown 0.35-mm lead equivalence is most effective;^{18,19} however, this was the only thickness of thyroid shield tested. The better performance of Design 2 for the superior slice may have been owing to a better neck adjustment, and the lateral aspects of the neck are shielded using this design, since the neck straps also contain shielding materials.

Figure 5 Error bar chart for the thyroid gland. The x-axis shows the different scenarios. The y-axis shows the average dose (mGy) and the 95% confidence interval (CI) for each scenario.

Table 2 Percentage dose reduction for the two slices and for the thyroid gland

Thyroid gland level studied	Design of thyroid shield				
	1	2a	2b	2c	3
Superior slice	34%	43%	43%	46%	20%
Inferior slice	38%	34%	27%	28%	10%
Whole thyroid gland (superior + inferior slice)	35%	41%	40%	42%	17%

Figure 6 The thyroid shield causing some artefact at the most inferior aspect of the image.

Shield 3 is described as disposable. There are no bands to attach this shield to the patient and would be best employed when the patient is in a supine position, limiting its use in CBCT devices. Thyroid Shield 3 showed the least dose reduction compared with the other thyroid shields. This could be owing to the thickness, smaller size and decreased coverage of the thyroid gland in all directions. However, it showed a statistically significant difference to the thyroid shield-free scenario.

It has been suggested that the entire circumference of the neck should be covered in thyroid shielding, as in many CBCT devices the X-ray beam rotates 360° around the patient, and not only the anterior of the head and neck. It was decided not to fully cover the posterior neck in the present study since there were no commercially available thyroid shields of that design. Qu *et al*,^{18,19} demonstrated in adult patients no significant thyroid dose reduction can be obtained in an adult phantom when shielding this area with an extra thyroid shield.

A counterproductive effect has been found when using thyroid shielding in conventional CT examinations, where the automatic exposure control (AEC) detects the presence of the shield and increases the tube current, thereby decreasing the effectiveness of dose reduction for the thyroid gland.²⁶ A single study in dental CBCT on dose reduction of the thyroid gland and the use of an AEC (NewTom 9000; QR, Verona, Italy), Tsiklakis *al*,²⁷ showed a 45% dose reduction when using thyroid shielding. This study indicates the presence of the thyroid shield did not influence the exposure factors when performing the scan. Therefore, it would be interesting to compare the dose reduction in a CBCT machine with an AEC *vs* no AEC in a child phantom.

This study did reveal minor artefacts owing to the presence of the thyroid shield (Figure 6); however, the

magnitude of these artefacts depends on the material and the impact it has on the image quality and diagnostic task. Collimation of the X-ray beam is a powerful tool for dose reduction,^{14,28} the effect of thyroid shielding with a small FOV of 6 × 6 cm or less remains uncertain. However, it is expected the efficacy of thyroid shielding to be lower than in large FOVs. Goren *et al*,²⁹ demonstrated that collimating the beam from a large FOV to a maxillary FOV only can reduce the dose to the thyroid gland by up to 70%.

In conclusion, in the context of dental CBCT imaging, thyroid shielding has been shown to be effective in dose reduction to the thyroid gland in a paediatric phantom when large FOVs are used. The degree of dose reduction is dependent upon the design of thyroid shield and lead thickness. However, in all clinical scenarios, the dose reduction by a thyroid shield was of statistical significance compared with the thyroid shield-free scenario. Therefore, it should be recommended to use thyroid shielding in child patients when undertaking large FOV CBCT scans. The study also found that a shield of 0.25-mm lead-equivalent thickness offered as good thyroid protection as a shield of 0.50-mm lead-equivalent thickness. Lead shielding material performed just as well as more expensive non-lead-equivalent materials. A thyroid shield that wraps around the neck may be beneficial to aid further dose reduction. Further studies are required to include a wider range of thyroid shields to determine which factor best influences the dose reduction.

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