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RESEARCH ARTICLE

The use of a thyroid shield for intraoral anterior oblique occlusal views—a risk-based approach

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Objectives: To estimate the radiation dose reduction to the thyroid for an anterior oblique occlusal view from the use of a thyroid shield, compare this with the variation in thyroid dose resulting from differences in examination positioning and discuss the additional considerations associated with the use of a thyroid shield before making a recommendation on their routine use for this examination.

Methods: Doses to the oral mucosa, the salivary glands, the thyroid, the extrathoracic airways, the oesophagus and the lungs were directly measured for anterior oblique occlusal X-rays of a Rando phantom with and without a thyroid shield using strips of calibrated XRQA Gafchromic film. The examination was also simulated using Monte Carlo software for the without thyroid shield case for a comparison of the dose and to evaluate the dosimetric effect of suboptimal examination positioning.

Results: A 36% reduction in thyroid dose was measured as a result of thyroid shield use; the effective dose reduction is of the order of 22%. Suboptimal positioning was found to increase thyroid dose by a far more significant amount.

Conclusions: Despite the reduction in thyroid dose, cost-benefit considerations mean that the purchase of a thyroid shield is only recommended where a very high number of anterior oblique occlusal views are undertaken. Optimization efforts for this examination are better focussed on training in examination positioning.

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Introduction

In UK, the Ionising Radiations (Medical Exposure) Regulations 2000¹ require that patient doses resulting from radiodiagnostic examinations be “as low as reasonably practicable consistent with the intended purpose”. This requires each examination to be optimized, which includes considerations relating to the choice of X-ray generating equipment, detector, exposure factors, beam and patient positioning and patient shielding. The as low as reasonably practicable principle comes from the recommendations of the International Commission on Radiological Protection (ICRP)² as it is synonymous

with their “as low as reasonably achievable” (ALARA) principle. The ICRP intend that ALARA have “social and economical factors taken into account”. Hence, when considering optimization locally, financial considerations along with an assessment of any potential non-radiation risk introduced by any of the measures intended to reduce patient exposure should be included.

For intraoral examinations, opinion is divided on whether or not to provide the patient with a thyroid shield. Some formal guidance states that best practice is to give the patient a thyroid shield wherever possible.³⁻⁵ Other guidance states that the provision of thyroid protection is likely to only be of use for those views where the thyroid could be in the primary beam.⁶⁻¹⁰ The

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latter state that the decision should involve consultation with the local medical physics expert or equivalent.

The medical physics expert will give their advice based in part on their understanding of the reduction in absorbed dose to the thyroid as a result of using a thyroid shield. Many studies have tried to quantify this; Sikorski and Taylor¹¹ for a full mouth intraoral series, Schmidt et al¹² for a periapical and Hoogeveen et al¹³ for upper anterior views. Both Sikorski and Taylor¹¹ and Hoogeveen et al¹³ suggested that thyroid shields should be used for the views they studied whilst Schmidt et al¹² suggested that thyroid shields were not a reasonable measure for the views they studied. The authors cannot find any study that has explicitly investigated an anterior oblique occlusal view (also known as a standard occlusal view), although, Hoogeveen et al¹³ did suggest that since their results indicated the use of a thyroid shield for upper anterior views this would be equally true of occlusal views. Whaites and Drage¹⁴ recommend that a thyroid shield be used for anterior oblique occlusal views.

It is the author's intention in this work to estimate the dose saving to the thyroid for an anterior oblique occlusal view as a direct result of the use of a thyroid shield, to compare this with the variation in thyroid dose resulting from differences in examination positioning, to consider economic factors and to discuss the additional considerations associated with the use of a thyroid shield before making a recommendation on whether or not thyroid shields should be used routinely for this view.

Methods and materials

Choice of phantom

The head, neck and chest of an Alderson Rando anthropomorphic phantom (The Phantom Laboratory, Salem, NY) were used for all of the measurements in this work. The Rando phantom is made of tissue equivalent materials that follow the International Commission on Radiation Units report 44¹⁵ and is constructed in slices so as to allow for the placement of thermo luminescent detectors (TLDs) within. Whilst Rando is made of tissue equivalent materials, any measurement made within the Rando phantom is not going to be the same as that in an equivalent position in a patient. This is owing to anatomical differences between Rando and a patient; of most relevance to dental work, Rando does not have an oral cavity. Given this, it would be expected that there will be more attenuation of the radiation from an anterior oblique occlusal view near the point of radiation entering the body with Rando than for a real patient.¹⁶ Conversely, the fact that no image receptor can be placed inside the phantom will mean that there is more transmission than would be expected for a patient during a real examination.

Nevertheless, in an assessment of whether or not a thyroid shield reduces the dose to the patient's thyroid during an anterior oblique occlusal examination, this

does not matter. As long as the same phantom is used in both cases, with the same X-ray beam and radiation detector positioning, the difference in results between the with and without thyroid shield cases will be accurate, even if the estimation of the absolute thyroid dose is inaccurate.

Choice of detector

Previous work in quantifying the reduction in the absorbed dose to the thyroid with thyroid shields has used TLDs,¹² film¹¹ and a Raysafe Xi survey detector.¹³

The small size of TLDs means that the measured dose only reflects that over a very localized area. To build up an idea of the dose distribution throughout the phantom, lots of TLDs are required allowing values of dose at any point to be interpolated from the measured values. However, accurate sampling of the distribution in this case would require TLD placement that is much closer together than the predrilled holes of Rando allows for.

The RaySafe Xi survey detector (RaySafe AB, Billdal, Sweden) has a significant energy dependence. The use of the detector in a different beam quality from that in which it was calibrated requires that a correction factor, k_Q , be applied to account for the differences in detector response in the calibration and use conditions.¹⁷ In normal use with dosimeters, it is not common practice to apply k_Q as it is generally very close to unity. The energy dependence of the detector, and Hoogeveen et al's¹³ unusual use of the detector, are such that this is not the case. Local measurements made with RaySafe Xi survey and R/F detectors demonstrated that whilst the two agreed to within $\pm 3.5\%$ in a free in air geometry, the survey detector measured 21% higher than the R/F detector when the two were placed between two 5-cm blocks of Solid Water HE (Gammex, A Sun Nuclear Company, FL). The R/F detector is known to have less energy dependence than the survey detector, and theoretical calculations of the expected attenuation from the Solid Water agree closely with the result measured by the R/F detector. It is concluded that for the beam quality used in the work of Hoogeveen et al¹³ the value of k_Q that should have been applied to the result from the survey detector is likely to have been close to 0.82. It is acknowledged that this has no effect on their calculation of the dose reduction from the use of a thyroid shield but it does affect their estimation of absolute dose.

The detector used throughout this work is XRQA 2 Gafchromic film (Ashland, Ashland Global Holdings Inc., Covington, KY). This radiochromic film is self-developing upon irradiation in a manner that is proportional to the quantity of radiation used to expose it. Therefore, it can be used for making dosimetric measurements. It is sold in sheets that are 25 × 30 cm in size but can be cut to any smaller shape without affecting its performance. Where large strips of Gafchromic film were placed in between slices of the Rando phantom, a

dose distribution over the whole area can be determined from a single film.

Gafchromic film has been widely used throughout diagnostic radiology and interventional radiology for everything from quality control measurements to quantifying patient entrance skin dose.^{18–22} It has also been used for dose measurements in intraoral radiography.^{23,24} Such widespread use means that the optimal technique for using the film has been determined and shared. The optimal use of the film requires it to be given enough time to fully develop post-exposure, to be stored correctly pre- and post-exposure, to be exposed to a minimum dose in order to exhibit a stable response to exposure and to be digitized in a specific way to be useful for dose estimation. All of the recommendations made elsewhere with regards to the optimal use of the film²⁵ were adhered to throughout this work.

Intraoral X-ray unit

All X-ray exposures in this work were undertaken on a Sirona Heliodont DS intraoral X-ray unit with fixed 60 kV, 7 mA and variable time. The half value layer (HVL) of the unit was measured to be 1.94 mm of Aluminium at 60 kV and stated as 1.9 mm of Aluminium by the manufacturer. It was installed in 1998, has been in routine clinical use ever since and is subject to biennial testing by NHS Tayside's Radiation Physics department and more frequent quality assurance (QA) testing by local users. At the time of this work, the unit's testing was up to date and it was performing within the manufacturer's specifications.

Gafchromic film calibration

An estimation of dose from the response of the Gafchromic film to radiation exposure is only possible with an accurate calibration. Gafchromic film exhibits a variable response to exposures made at different kV_ps and of varying beam qualities (defined by their HVL). Therefore, the calibration needs to mimic the exposure conditions of the phantom exposures as closely as possible to be accurate. The aim was to calibrate the Gafchromic film over a dose range of 0.5 to 5 mGy as this would cover the full range of measurements made throughout the phantom work. The XR QA 2 Gafchromic film is stated by the manufacturer as having a useful range of 1–200 mGy, although, the film has been found to have a useful range beginning at 0.5 mGy locally.

A RaySafe R/F detector was placed between two 5-cm blocks of Solid Water HE and an exposure made at 0.5 s. Three measurements were taken to ensure there was excellent repeatability between exposures. Each single exposure was less than 0.5 mGy; in order to achieve doses in the range of 0.5–5 mGy it is necessary to irradiate each piece of Gafchromic film multiple times.

A sheet of Gafchromic film was divided into 10 squares, each of which was placed in turn between

two 5-cm blocks of Solid Water HE. Each square of film was irradiated in turn at 0.5 s, the predetermined number of times to achieve a known and incrementally increasing dose between 0.5 and 5 mGy. In total, 10 calibration films were irradiated at approximately 0.5 mGy intervals.

The films were given enough time to fully develop (a minimum of 48 h) and then digitized using an EPSON reflective scanner—in keeping with optimal use of Gafchromic film, only the red channel of the scanned images was used and all scanner suggested image corrections were disabled.

Once digitized, measurements of the digital Gafchromic film images were made using the ImageJ software package US National Institutes of Health, Bethesda, MD).²⁶ A ROI was drawn on each film and the average pixel value recorded—the calibration of the film was created using the relationship between measured pixel values and measured exposure. The calibration curve was determined using MATLAB's (MathWorks, Natick, MA) cftool curve fitting toolbox.²⁷

Finally, a correction was required to the measured kerma to account for backscatter. The Raysafe R/F detector is lead backed, therefore, does not measure back-scattered radiation, but the Gafchromic film does. The increase in kerma as a result of backscatter was measured using a Radcal 6 cc ionization chamber (Radcal Corporation, Monrovia, CA) placed free in a free in air geometry and then on top of 5 cm of Solid Water HE. Both exposures were made at 60 kV_p, at the same focus to detector distance and with the same exposure time. The difference in these measurements of kerma can be attributed to backscatter. It is worth noting here that the ionization chamber could not have been used for all of the calibration exposures because it would have required the application of an unknown, but likely significant, k_Q factor.

Exposures of Rando

Five large strips of Gafchromic film were placed in between adjacent slices of Rando that corresponded to just below the mouth, the salivary glands, the top of the thyroid, the base of the thyroid and the apex of the lungs, as can be seen in [Figure 1](#).

The intraoral X-ray set described in “Intraoral X-ray unit” was used for all of the exposures. The rectangular cone of the intraoral unit was positioned for an anterior oblique occlusal by a superintendent dental radiographer with 33 years of experience, as per [Figure 2](#). A tilt angle of 65° was used, in line with best practice.¹⁴ Markers were placed on the top of Rando's head to aid with precise reproducibility of cone position for the with and without thyroid shield cases, since it was necessary to take Rando apart in-between to replace the Gafchromic film strips.

The exposure factors used clinically on this unit for an anterior oblique occlusal view (60 kV, 7 mA, 0.5 s producing a measured entrance dose without backscatter of 1.35 mGy) were used to perform the examination



Figure 1 The XRQA Gafchromic film positioned within the Rando phantom.

on Rando. The examination was performed 30 times consecutively—this was necessary to increase the exposure of the Gafchromic film to above the minimum threshold of its stable range and into the range that had been calibrated earlier.

Once 30 exposures had been performed, the Gafchromic films were replaced with fresh strips—it was necessary to tightly trim these to the contours of the Rando phantom so that the thyroid shield was not pushed to an unnatural position when it was placed around Rando. The thyroid shield was of 0.35 mm lead equivalence. The cone of the intraoral unit was positioned as before using the markers previously placed on top of Rando's head to ensure reproducibility. A further 30 exposures were made.



Figure 2 The intraoral X-ray tube positioned for the anterior oblique occlusal view.

Analysis of irradiated Gafchromic film for thyroid dose assessment

The irradiated films were allowed to fully develop and then digitized using the same process as for the calibration films.

Once digitized, the images were imported into ImageJ. A line profile was drawn on each film extending from the front to the back along the central axis of the X-ray beam (*i.e.* the plane of highest radiation dose) to examine the variability with depth. Using an ImageJ contour plotter plugin²⁸ contours were drawn on the image that correspond to levels of equivalent exposure. This gives a visual representation of the dose distribution throughout each film along both axes. This image also indicated the most uniform area to make an average measurement of pixel value in an area equivalent to the thyroid using a ROI drawn by the user. These were generally placed in an area that corresponded to 2 cm into the Rando phantom.

The average pixel value for any ROI that corresponds to the location of an organ can be used with the Gafchromic film calibration to produce a result for the measured absorbed dose to that organ. The absorbed dose to the thyroid, in μGy , was estimated by taking the average pixel value in a region that corresponds to the estimated position of the thyroid and using the Gafchromic film calibration.

Software estimation of the absorbed dose to the thyroid and effective doses

PCXMC²⁹ (STUK - Radiation and Nuclear Safety Authority, Helsinki, Finland) is a Monte Carlo program for calculating patient organ and effective doses in radiographic X-ray examinations. The anatomical data for the program come from the mathematical adult hermaphrodite phantom models of Cristy and Eckerman³⁰ which are slightly amended for more realistic external exposure conditions. Full control is given over the external X-ray beam; everything from size, position, angulation and beam quality (kV_p , beam filtration and anode angle). It is not possible to add additional features however; therefore, only the anterior oblique occlusal views without the thyroid collar could be simulated.

An anterior oblique occlusal view that was equivalent to that performed on the Rando phantom was simulated in PCXMC using 60 kVp, a filtration of 2.03 mm Al (calculated using a measured HVL of 1.94 mm Al and an assumed anode angle of 12°). An air kerma of 1.35 mGy (that measured for the intraoral unit using exposure factors of 60 kVp, 7 mA and 0.5 s) was used. The geometry was as shown in Figure 3, a screenshot from the PCXMC program. This was deemed to be as close to the exposure undertaken on the Rando phantom as possible. The program returned organ doses for all of the organs contained in the phantom and an effective dose.

Variations were made to the simulation to determine the effect they would have on the patient's organ and

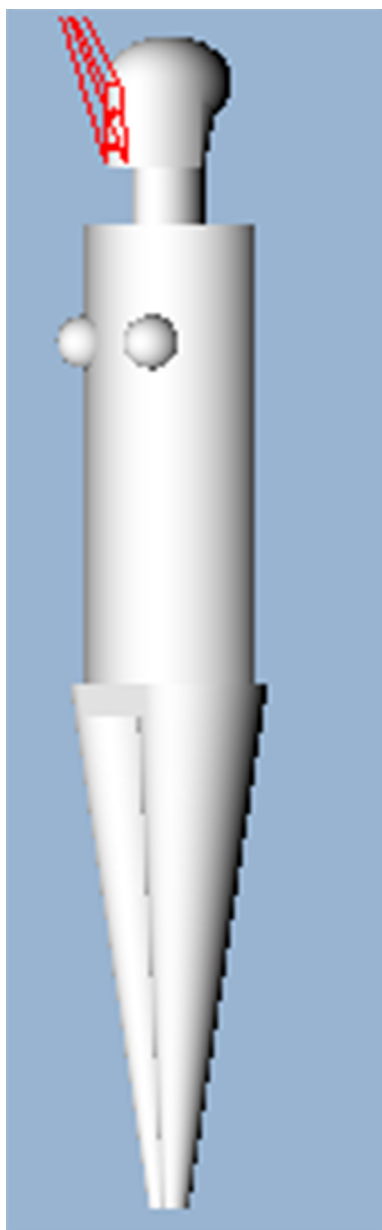


Figure 3 . The geometry of the anterior oblique occlusal view in the PCXMC program.

effective doses. These changes were intended to represent variances in positioning practice that could be observed in the dental surgery.

Changes were made to the z-axis centring; the first exposure was deemed to be optimally centred, subsequent exposures moved the centre downwards in 1 cm increments from 1 to 5 cm. This was deemed to cover all realistic cases of slightly suboptimal positioning to very poor positioning, with the worst case illustrated in [Figure 4](#). In this case, the whole of the thyroid is clearly in the path of the primary beam.

Variations were made of the cranial caudal angle; the first exposure had an angle of 65° and was deemed to

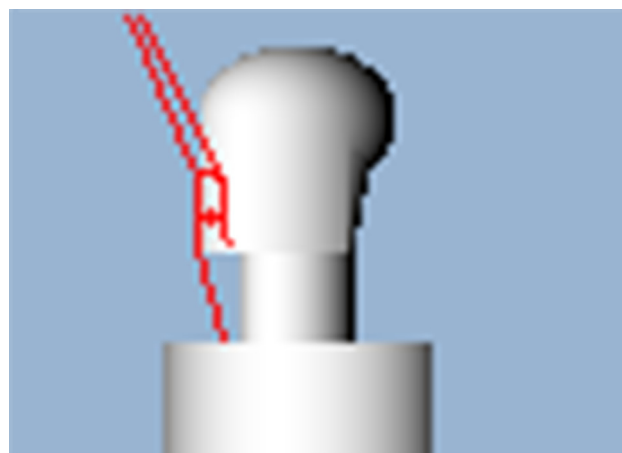


Figure 4 The geometry of an anterior oblique occlusal view with poor height centring in PCXMC.

be optimal. Further exposures varied the angle between 55° and 75° in 5° increments. This was deemed to cover all realistic cases of slightly suboptimal positioning to poor positioning, with the worst case illustrated in [Figure 5](#). In this case, the whole of the thyroid is clearly in the path of the primary beam.

Finally, some variations were combined in order to find the worst case effect on patient organ and effective doses. These included combinations of a reduction in centring height by 5 cm and a cranial caudal angle of 60° and then 55°.

As with the Gafchromic film exposures with Rando, it should be noted that these simulations did not include an image receptor. Therefore, the calculated dose to all organs can be regarded as an absolute worst case.

Estimates of effective dose using measured doses

The ICRP define effective dose as the sum of all individual organ absorbed doses multiplied by a radiation weighting factor (which is unity for X-rays) and a tissue weighting factor.² To estimate the effective dose for the anterior oblique occlusal examinations undertaken with and without the thyroid shield, absorbed doses were estimated for the oral mucosa, the salivary glands, the thyroid, both extrathoracic airways, the oesophagus and

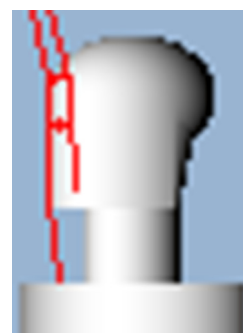


Figure 5 The geometry of an anterior oblique occlusal view with poor cranial caudal angulation in PCXMC.

the lungs using ROIs on the Gafchromic films that corresponded to the approximate position of each organ.

The absorbed dose to all other organs in the body (which were not measured using Gafchromic film), were calculated using the PCXMC program and were taken to be the same for the with and without thyroid shield exposure. This is a valid assumption, since internal scatter does not reach much beyond the range of organs under consideration in this work and external scatter is much reduced outside the same range.

With an estimate for absorbed dose—obtained from measurement for the exposed organs and simulated for the organs that received little or no exposure—for all of the organs used by the ICRP in their definition of effective dose now available, the relevant tissue weighting factors were applied and an effective dose for the with and without thyroid shield cases calculated, in μSv .

Results

Gafchromic film calibration

Despite working at and just above the minimum threshold for stable film response to radiation, a good exponential fit for film calibration was achieved, with an R^2 of 0.969 reported by MATLAB. Whilst it has been demonstrated possible to achieve an R^2 of greater than 0.99 when working comfortably within the film's operational range (*i.e.* tens of mGy),³¹ the calibration obtained for this work covered the full range of exposures encountered within the film irradiated in Rando. Since no extrapolation of the calibration was required, the uncertainty of results derived using the calibration is reduced.

Rando Gafchromic film exposures

An assessment of dose with depth: Figure 6(a–e) shows the change in dose with anteroposterior depth where zero is the phantom entrance for the Gafchromic film positioned (a) just below the mouth, (b) the salivary glands, (c) the top of the thyroid, (d) the base of the thyroid and (e) the apex of the lungs corresponding to the visible film strips in Figure 1. The black line represents the dose without a thyroid shield, the red line represents the dose with the thyroid shield. Figure 6f is a lateral view of the Rando phantom; the horizontal lines represent the locations at which the Gafchromic film was placed. The topmost four vertical lines indicate a depth of 60 mm into the phantom from the entrance surface to help the reader visualize the dose distributions shown in Figure 6a–d within the phantom; the bottom-most vertical line indicates a depth of 40 mm into the phantom from the entrance surface to compare with the dose distribution shown in Figure 6e.

The thyroid shield does not cover the mouth, therefore, the with and without thyroid shield exposures should be very close. Figure 6(a) demonstrates that this is the case. A peak dose of 28–35 μGy can be seen at the skin;

this decreases moving into the phantom and flattens out around 12 μGy at a depth of 4–6 cm. A large ROI (centred on the central axis but extending equally to both right and left) placed at a 2-cm depth records an average dose of 12.48 and 12.54 μGy for the with and without thyroid shield exposures. This level of agreement gives confidence that the exposure levels experienced by the phantom with and without the thyroid shield were very similar and that the measures taken to ensure accurate repositioning were effective.

A properly worn thyroid shield would be expected to reduce the dose to the salivary glands partially by direct protection but predominantly by way of reducing the amount of radiation in the area below that could scatter upwards. This is demonstrated to be the case in Figure 6(b). At a superficial depth, the trend in increasing dose is the same for both exposures but the dose level is almost half with the thyroid shield in place. This is the contribution of direct protection from incident radiation. With increased depth, the dose without the thyroid shield is observed to continue increasing—this is a result of direct irradiation combining with internal scatter from above and below. The thyroid shield removes some of the incident radiation at and below the salivary glands thereby reducing the internal scatter. Therefore, the dose is observed to steadily decrease with depth. A large ROI (centred on the central axis but extending equally to both right and left) placed at a 2cm depth records an average dose of 13.7 and 18.2 μGy for the with and without thyroid shield exposures

The dose at the top of the thyroid follows a similar pattern to that at the salivary glands. At a superficial depth, the trend in increasing dose is the same for both exposures but the dose level is around two-thirds with the thyroid shield in place. This is the contribution of direct protection from incident radiation. With increased depth, the dose without the thyroid shield is observed to continue increasing—this is a result of direct irradiation combining with internal scatter from above and below. The thyroid shield removes some of the incident radiation at and below the top of the thyroid thereby reducing the internal scatter, hence the dose steadily decreases with increasing depth. A large ROI (centred on the central axis but extending equally to both right and left) placed at a 2-cm depth records an average dose of 9.7 and 15.2 μGy for the with and without thyroid shield exposures.

The dose at the base of the thyroid follows the same trend at superficial depths; there is an increase in dose for both exposures but the dose with the thyroid shield is around half of that without the thyroid shield. The peak dose is reached at a depth of around 8–10 mm which is more superficial than for the organs considered so far. This is because the base of the thyroid is sufficiently far away from where the primary beam first enters the patient that there is less radiation reaching this far down at a depth greater than 10 mm. The peak around 8–10 mm is the result

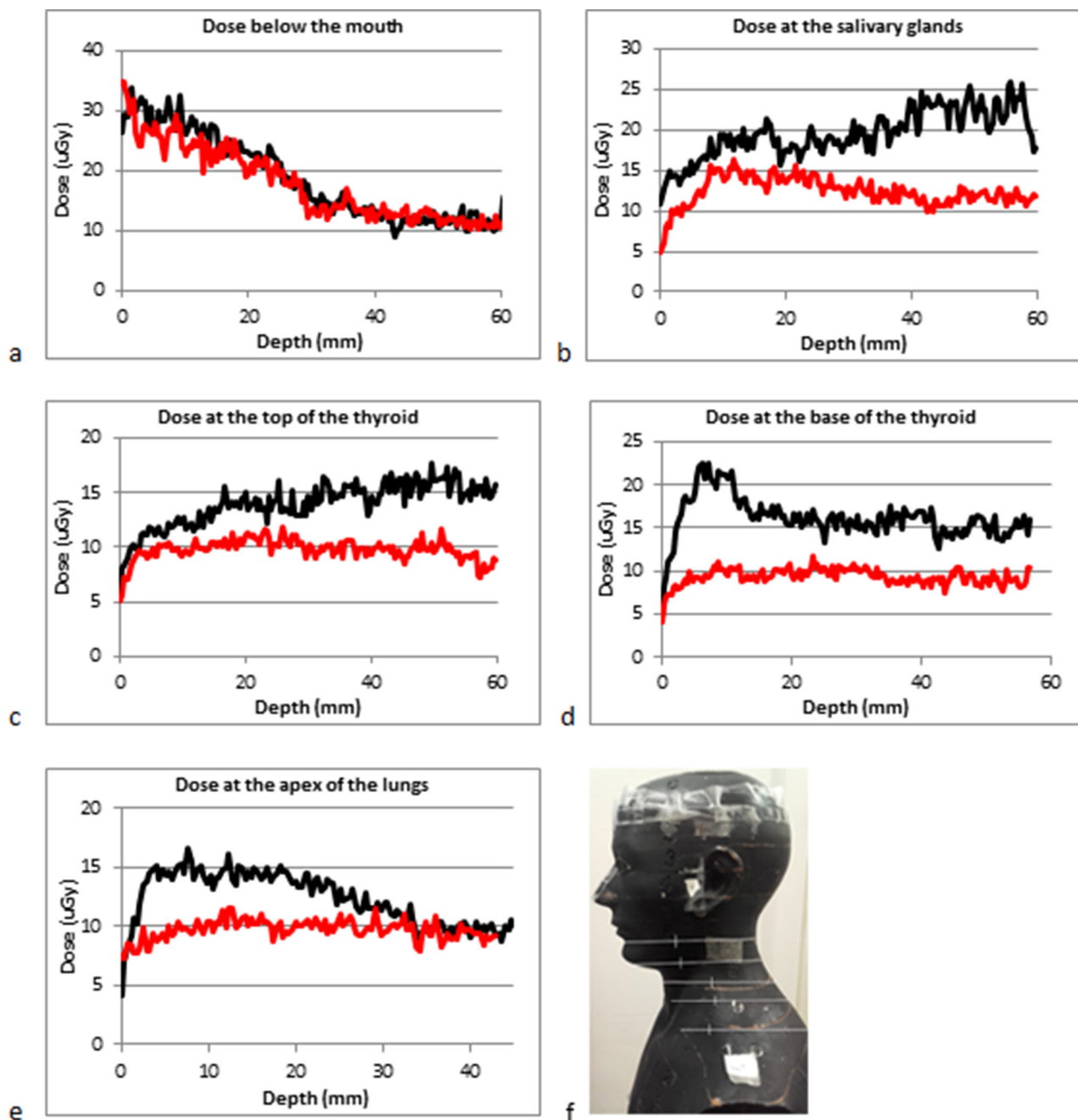


Figure 6 Dose with increasing anteroposterior depth of phantom at (a) just below the mouth, (b) the salivary glands, (c) the top of the thyroid, (d) the base of the thyroid and (e) the apex of the lungs. The exposure without the thyroid shield is shown in black, the exposure with is shown in red (f) a lateral view of the phantom; horizontal lines indicate the position of the Gafchromic film. The topmost four vertical lines indicate a 60 mm depth from the entrance surface of the phantom, the bottommost line indicates a 40 mm depth.

of some primary radiation and scatter from above and below. With the thyroid shield the peak is also around 8–10 mm depth, but around two-thirds the dose. The dose then remains steady moving deeper into the phantom, the result of scatter from above and below. A large ROI (centred on the central axis but extending equally to both right and left) placed at a 2cm depth

records an average dose of 10.5 and 16.2 μGy for the with and without thyroid shield exposures.

At the apex of the lungs, the trends are similar to those at the base of the thyroid. The peak dose is reached at a depth of around 8–10 mm and the dose with the thyroid shield is around two-thirds of the dose without. The dose without the thyroid shield is then observed to decrease moving deeper into the phantom because the

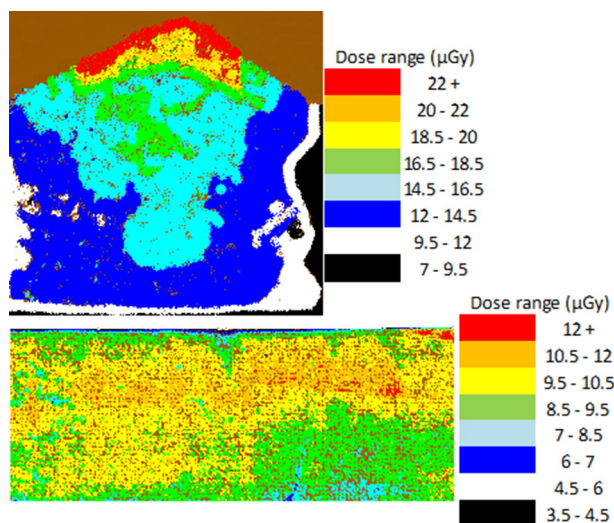


Figure 7 (a) The dose distribution at the base of the thyroid where no thyroid shield is worn and (b) with a thyroid shield. Radiation is incident from the top of the film at the centre. Dose levels are included in the key next to the image.

apex of the lungs is far from where the radiation first enters the patient so there is not as much reaching this far down at depths of greater than 10 mm. The peak is the result of some primary radiation and scatter from above and below. With the thyroid shield the peak is around 13 mm depth and around two-thirds the dose level. The dose remains steady moving deeper into the phantom, the result of scatter from above and below. A large ROI (centred on the central axis but extending equally to both right and left) placed at a 2cm depth records an average dose of 10 and 13.7 μGy for the with and without thyroid shield exposures.

An assessment of thyroid dose: Assessing the absorbed dose to the thyroid requires an examination of the three dimensional dose distribution across the whole organ, which is expected to vary such that it will decrease towards the posterior and the base of the gland. Using the Gafchromic film exposed at the base of the thyroid it is confirmed that this is the case in the anteroposterior plane, as can be seen in Figure 7 which contains isodoses created from the digitized films base without (a) and with (b) the thyroid shield. Note that, although, the colours remain constant, the scale changes between (a) and (b). The brown colour in Figure 7(a) is the Gafchromic film that extended in front of the phantom during the examination.

With the data that has been presented it is not possible to determine the absorbed dose accurately, although, an estimate of the dose reduction as a result of the thyroid shield is possible. Entrance skin dose reductions of the order of 38–50% were discussed in “An assessment of dose with depth”, however, the thyroid is not

positioned so superficially. Looking at the differences in dose measured using the ROI placed at a depth of 2 cm gives a reduction of 36.2% at the top of the thyroid and 35.2% at the base. These reductions are consistent enough to make their average, 35.7%, a reasonable representation of the absorbed dose reduction to the thyroid arising from the use of a 0.35 mm lead equivalent thyroid shield.

Effective dose assessment: By assigning one or more organs from those used by the ICRP in their calculation of effective dose² to each piece of Gafchromic film and using the dose results reported in “An assessment of dose with depth”, it is possible to estimate an effective dose for the exposure with and without the thyroid shield in order to estimate the extent of the reduction in effective dose as a result of the thyroid shield.

The organs used for this calculation were the oral mucosa, the salivary glands, the thyroid, both the extra-thoracic airways, the oesophagus and the lungs.

The absorbed dose to all other organs were calculated using the PCXMC program and were taken to be the same for the with and without thyroid shield exposure. This is a valid assumption, since internal scatter does not reach much beyond the range of organs under consideration in this work and external scatter is much reduced outside the same range.

The effective dose without the thyroid shield was calculated to be 7.0 μSv . With the thyroid shield, this reduced to 5.5 μSv . This represents a per examination effective dose reduction of 1.5 μSv —a reduction of 21.5%.

PCXMC estimated an effective dose of 8.4 μSv for a simulation equivalent to the without thyroid shield exposure. The difference between the simulated and calculated from measured organ doses effective doses is predominantly owing to the difference in dose to the oral mucosa; PCXMC estimated this as far higher than measured in Rando – this is to be expected since the mathematical phantom has an oral cavity whilst Rando attenuates much of the radiation in this area before it is measured. The measured and simulated doses to the thyroid were 15.7 and 7.2 μGy , respectively.

PCXMC simulations

For the simulation that best matched the work performed with Rando, the absorbed dose to the thyroid was calculated to be 7.2 μGy .

The lowering of the centre point of the X-ray beam in 1 cm increments up to 5 cm was found to significantly increase the dose to the thyroid, as would be expected given the thyroid is increasingly in the primary beam with each increment. Increases in absorbed dose to the thyroid were of the order of 41, 61, 105, 167 and 196% with each increment; as such, the absorbed dose to the thyroid becomes significantly increased with very poor positioning, although, even a slightly lower centre point position increases the absorbed dose to the thyroid by almost half. The effective dose is calculated to increase

with the absorbed dose to the thyroid, although, that increase is less at the 5 cm lower than optimal position than for the 4 cm position. This is owing to reduced absorbed dose to the brain, oral mucosa and salivary glands with less of an increase in the absorbed dose to the thyroid.

Changing the cranial caudal angle of the X-ray beam had a variable effect on absorbed dose to the thyroid and effective dose. At a 55° angle, there was a 5% reduction in absorbed dose to the thyroid because the angulation meant that less of the thyroid was in the primary beam. However, the effective dose increased by 17% owing to an increased dose to organs including the extrathoracic airways, the lymph nodes, the oral mucosa and the salivary glands. At a 60° angle there is a 41% increase in absorbed dose to the thyroid because more of the organ is in the primary beam. The effective dose increases by 21% as a result of the increased absorbed dose to the thyroid.

At a 70° angle, the absorbed dose to the thyroid reduces by 36% because less of the thyroid is in the primary beam. The effective dose reduces by 20% as a result of the reduced absorbed dose to the thyroid. At a 75° angle, these reductions are more so, with a 57% reduction in absorbed dose to the thyroid and a 38% reduction in effective dose.

So far each variation has been considered in isolation. As a measure of a worst case increase in absorbed dose to the thyroid, the combination of a poorly centred X-ray beam (5 cm lower than optimal) and a suboptimal cranial caudal angle (60°) was simulated.

The absorbed dose to the thyroid was calculated to increase by 667% to 48 µGy whilst the effective dose increased by 223% to 18.7 µSv.

Discussion

The thyroid dose from a well-executed anterior oblique occlusal is estimated as 15.7 µGy, with an associated effective dose of 7.0 µSv. There is no comparative literature for this view, although, this dose falls well within the wide range of thyroid doses found in the literature in the review paper by Holroyd³² for intraoral examinations. There is also broad agreement with the simulations run in PCXMC, where the thyroid dose was 7.2 µGy and the effective dose was 8.4 µSv.

The use of a 0.35 mm lead equivalent thyroid shield led to a reduction in dose to the thyroid of 35.7% to 10.3 µGy and a reduction in effective dose of 21.5% to 5.5 µSv for this view.

As there was no image receptor used in this work, these doses can be presented as worst case since there was far more transmission of the primary beam than would be the case in a clinical examination.

The simulated exercise on the effect of suboptimal positioning demonstrated that lowering the centre of the X-ray tube by 1 cm increases the thyroid dose by 41%. The increase in thyroid dose is significantly worse the

lower the X-ray tube centring, rising to a 196% increase at 5 cm lower than optimal. Reducing the cranial caudal angle by just 5° to 60° leads to a 41% increase in thyroid dose. The combination of reduced angulation and lower centring was found to lead to an enormous increase in thyroid dose.

The increase in thyroid dose for even the smallest changes to centring or angulation is higher than the magnitude of the reduction with the use of the thyroid shield. This implies there are greater gains to be made in thyroid dose reduction with training and audit on optimal positioning than simply with the use of a thyroid shield alone. Even where a thyroid shield is used, in cases of suboptimal positioning its performance is unlikely to match the level reported in this work because it will be less effective in shielding against the higher average energy of the poorly aligned X-ray beam.

The ICRP's definition of ALARA includes "social and economical factors taken into account"; therefore, it is appropriate that there be a financial consideration when deciding upon whether or not to use a thyroid shield.³² The man-Sievert is a monetary value placed upon saving a population dose of 1 Sv and is a concept that is widely used for the protection of staff. Some countries choose to adopt several values, each referring to a specific level of dose, with their thinking that it is appropriate to spend more money to reduce a high dose to a moderate dose than a moderate dose to a low dose. This fact notwithstanding, internationally there is a wide variation in the adopted value. An information system on occupational exposure review of values in 2012 demonstrated this wide variation, reporting values from 13 to 3170k Euros per man-Sievert.³³ There is some consensus on a value of 50k Euros.³⁴

The use of the man-Sievert for patients undergoing X-ray examinations is more controversial. The data used for risk models is mostly from occupational or public exposure that was of no benefit to the individual. X-ray examinations are justified which is a process that includes weighing the benefits against the risks, which include the radiation exposure. In 1986, the (then) National Radiological Protection Board (NRPB) recommended values for the man-Sievert.³⁵ These were set at 50k Pounds per man-Sievert for occupational exposures and medical exposures of the general population, 100k Pounds per man-Sievert for medical exposures of the paediatric population and 10k Pounds per man-Sievert for medical exposures of the geriatric population. Whilst these proportional values match the risk profile for these populations, the differences are of limited practical use outside of specialist facilities since the same equipment is used on all patients. This demonstrates one of the drawbacks of using the man-Sievert model in diagnostic radiology. Another is public perception, as noted by the authors of the Institute of Physics and Engineering in Medicine's report 82³⁶ in that the nuclear industry have higher values for man-Sievert owing to public pressure, whereas the values are lower

in healthcare owing to an appreciation of budgetary constraints and competing demands for money that could result in a much higher benefit to individuals or the population if used elsewhere. In this fashion, a wide range of values for the man-Sievert could be justified within defined parameters.

In 1990, the NRPB recommended using the man-Sievert to prioritize equipment replacement, focussing on selecting equipment that had lower costs per man-Sievert averted.³⁷ The NRPB acknowledged, however, that it is difficult to convince a Health Service Manager to spend limited resources where the saving—in blunt terms of a few potential delayed deaths—is not readily apparent. They proposed alternatives, such as measuring cost effectiveness in terms of the cost per quality adjusted life year saved or a cost utility analysis with the outcome expressed in terms of life years gained, ideally also adjusted for quality.³⁷ As of now, there is little consensus on how best to apply any kind of financial reasoning to decisions regarding the optimization of X-ray exposures.

As an illustrative exercise using a value of 50k Euros per man-Sievert, the effective dose saving of using a thyroid shield for one single anterior oblique occlusal (1.5 μ Sv) is such that the thyroid shield would need to be used for over 7000 anterior oblique occlusal views over its lifetime before being considered a worthwhile expenditure for optimization. This would require an unusually high workload of anterior oblique occlusal examinations, and it is likely that many of the patients who would have been referred for this examination may now be referred for dental CBCT as the availability of this technology grows.

This means that the purchase of a thyroid shield is not a cost effective means of optimization unless the department or surgery performs a very high number of anterior oblique occlusal views. The estimates of effective dose used for the risk-benefit analysis throughout this work have all been for adults. The risk from an equivalent exposure is higher for paediatrics, and there are also patients with a fear of radiation to be considered, for whom the risk-benefit ratio is different. For these patient cohorts, each case needs to be considered on its individual merits, in many cases it may prove beneficial to refer these patients to a specialist facility (*e.g.* a dental hospital) better equipped to perform the examinations on these patient. These facilities are also more likely to have dental CBCT and may choose to use it instead.

Thyroid doses from dental CBCT examinations have been found to vary widely with equipment, examination, exposure factors and FOV. Typical thyroid doses for adults have been measured ranging from 0.33 to

6.3 mGy.³⁸ Thyroid shields have been shown to be effective in some cases in reducing the dose to the thyroid by around 44%,³⁹ yet there remains disagreement as to whether or not thyroid shields should be used routinely with dental CBCT.^{4,40} Given the increasing number of dental CBCT examinations, the level of thyroid dose for these examinations and the higher potential for dose reduction through improved examination technique, optimization efforts are better focussed on these examinations.

It could be the case that a department or practice already has a thyroid shield, or that it is justified in purchasing one because it can be used for a multitude of different examinations making its purchase cost-effective. These departments must further consider the infection control issues arising from the use of a thyroid shield across many different patients and the ease and efficacy of a cleaning regimen for the garment. Since there is direct contact with the patient's skin, cleaning between each use is appropriate. Further specific considerations must be made for patients with open wounds or who are immunocompromised.

Furthermore, any practice that uses personal protective equipment is required under the ionizing radiations regulations 1999⁴¹ to ensure that it is properly used, stored and maintained. Guidance on the use of personal protective equipment in diagnostic radiology issued by the British Institute of Radiology⁴² suggests that thyroid shields need to be properly hung when not in use and periodically tested, ideally using a fluoroscopy unit. This introduces significant additional costs that must be considered.

Conclusions

The use of a thyroid shield for anterior oblique occlusal intraoral examinations has been evaluated with respect to the reduction in thyroid and effective dose. There is a dose reduction to the thyroid of around 36% with an associated decrease in effective dose of 22%. In absolute terms, however, these reductions are small enough that the purchase of a thyroid shield for this purpose is unlikely to be a cost-effective means of optimization unless the department or surgery performs a very high number of anterior oblique occlusal views. Those who do choose to use a thyroid shield must consider the provision and cost of appropriate storage, a thorough cleaning regimen and arranging periodic fluoroscopy testing. It has been demonstrated that suboptimal positioning for this examination can significantly increase the dose to the thyroid. Optimization efforts for this examination are likely to be better focussed on training and audit of examination positioning for all operators.

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