RESEARCH ARTICLE

Ambient dose during intra-oral radiography with current techniques: Part 2 quantifying the remnant beam - an in vivo study

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Objectives: (1) To find a safe reference transmission factor for the remnant beam to be used when assessing the remnant beam during intra-oral radiography. (2) To identify factors such as exposure type, side (left or right), gender and age that might significantly affect transmission.

Methods: Measurements were performed in the remnant beam during 323 intra-oral exposures of 43 patients. The exposure parameters were 60 kV and 7 mA. These measurements were compared with values in the same setting, but without a patient present to arrive at a transmission value. Differences between types of exposure [bitewing (BW), incisor and canine (IC) periapical, premolar and molar (PM) periapical], exposure side (left or right), gender and age were statistically analysed. The reference value was based on the exposure yielding the highest transmission value, to which a safety margin of two standard deviations (SDs) was added, and then rounding up.

Results: The respective mean transmission values (SD) for BW, IC and PM exposures were as follows: 1.78% (1.15%), 0.639% (0.63%) and 2.60% (0.98%). The differences between PM and IC and between BW and IC were significant ($p > 0.01$). The differences between exposure side, gender and age were not significant. The reference transmission value, which was calculated from the highest mean transmission percentage for PM (2.60%) plus twice the SD (0.98%) and rounding up, was 5%.

Conclusions: A transmission factor of 5% could be used to assess the remnant beam during intra-oral radiography. Anterior exposures led to significantly lower transmission values than posterior exposures.

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Introduction

The use of ionising radiation in the dental office is subject to rules and regulations regarding radiation protection.¹ These prescribe conditions pertaining to justification and optimisation of X-ray use, and compliance with dose limits. The dose limits are generally based on the recommendations of the International Commission on Radiological Protection.²

The limits are expressed as millisieverts per year, and vary for radiological workers, the public and the environment.² A radiation protection expert (RPE) is responsible for verifying that the radiation burden of a dental facility is within the recommended dose limits. The RPE's evaluation of ambient radiation from intra-oral radiography performed in the dental clinic takes into consideration three fractions: scattered radiation, leakage radiation and the remnant beam. The description of how the conversion factor was derived for

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converting the workload of dental X-ray devices to the ambient scattered radiation dose was presented in part 1 of this series of articles.³ The amount of leakage radiation is specified by the manufacturer of an X-ray device and should be checked upon installation. It can be measured and is easily quantified in relation to the workload of the X-ray device.

This report describes a study of the radiation dose in the area of the remnant beam exiting the patient as an extension of the primary beam. To estimate the yearly dose in directions where the remnant beam is a factor to be considered, it is important for the RPE to know the radiation dose in the remnant beam. Earlier investigations found that a higher dose prevails in the remnant beam than in areas where only scattered radiation is present.^{4–6} One limitation of these studies is that they used phantoms to determine the dose in the remnant beam. The phantoms consisted of a human skull covered with tissue-equivalent material that interacted with radiation from the dental X-ray device in manner similar to that of the head of a living patient in the dental chair.⁷ The use of a radiological phantom for the assessment of scattered radiation seems appropriate. However, assessment of the remnant beam involves factors in the clinical situation that are very different from assessments that can be performed with the use of a phantom.

One factor is that the teeth of the phantom are in occlusion while in most clinical instances during intra-oral radiography the patient's mouth is open in order to accommodate the beam aiming device or the patient's finger or thumb that holds the image receptor. Another factor is the variability of the morphology of patients and their dentition. Whereas some patients might present with many metal restorations, others might be missing teeth and alveolar bone. These are all very relevant factors for the amount of radiation that is attenuated when passing through the oral region of the patient, and therefore can affect the dose of the remnant beam. A more realistic evaluation of the remnant beam than testing with the use of a phantom would be studying it in a clinical setting during intra-oral radiography of several patients.

The older studies were also limited in that the results were reported as organ doses for a bystander or in obsolete units. Also the method of calculation of the effective dose has changed. For example, the tissue-weighting factors have been changed.⁸ Changes in the focus-to-image-receptor distance, the tube voltages and the use of direct-current instead of alternate-current devices have also occurred over the course of time. All these limitations indicate that earlier research data are obsolete with regard to current ambient dose assessments of intra-oral radiographic procedures.

Therefore, this study aimed to evaluate the radiation dose in the remnant beam in the clinical environment during intra-oral radiography. By quantifying the transmission of X-rays through the average patient and adding a margin of safety of two standard deviations

(SDs), we can provide the RPE with a transmission factor that can be applied to the original X-ray beam to arrive at a realistic dose from the remnant beam. The secondary aim was to establish if the transmission factor is affected by such factors as type of exposure (bitewing, posterior periapical, or anterior periapical), side (left or right), or patient gender or age.

Methods and materials

This *in vivo* study was conducted at the Department of Oral and Maxillofacial Radiology in our institution. Adult patients that were referred to the department for intra-oral radiography were asked to participate. Participation did not result in additional exposure to X-rays. Each patient provided signed, informed consent after being educated about the procedures. A number was assigned to each patient. The study was approved by the Medical Ethical Review Committee of our institution under registration number 2017005. Measurements were performed between February and December 2017 by one of the authors of this paper (CP).

The X-ray device used in this study was an Instrumentarium Focus (Instrumentarium Dental, Tuusula, Finland). The exposure parameters were as follows: tube voltage 60 kV, tube current 7 mA and total filtration 2.5 mm aluminium. It was equipped with a rectangular collimator of 3.5 × 4.5 cm, with a focus-to-end-of-tube distance of 30.5 cm. The exposure times are shown in Table 1. The output and timer of the X-ray generator were tested (5×) by a ThinX dosimeter (Unfors RaySafe AB, Billdal, Sweden). The parameters tested during the output test were kV, exposure time and dose at the end of tube in Gy/mAs.

The image detector used in the experiment was a phosphor storage plate (PSP) (VistaScan Image Plates Plus; number 1 and 2 Dürr Dental AG, Bietigheim-Bissingen, Germany). Beam-aiming devices of synthetic material (X-Act; ACTA, Amsterdam, Netherlands) were used to position the PSP intra-orally and to aim the X-ray beam at the PSP. With these aiming devices, the total focus-to-film distance was 40.5 cm.

For the experiments, the X-ray device was equipped with a custom-made plywood extension, to which a RaySafe Xi Survey Detector (Unfors RaySafe AB, Billdal, Sweden; calibration date: 2015-12-09) was fixed (Figure 1). The dosimeter contained silicon diodes

Table 1 Exposure times

	Molar	Premolar	Canine	Incisor	Bitewing molar	Bitewing premolar
Superior	0.25	0.16	0.1	0.1	0.2	0.16
Inferior	0.16	0.12	0.1	0.08		

Exposure times in seconds that were used for intra-oral exposures of patients.

Other parameters were: 60 kV tube voltage, 7 mA tube current and 40.5 cm focus-to-image-receptor distance.

Figure 1 The plywood extension mounted to the Instrumentarium Focus X-ray machine with the attached dosimeter, with its active surface in the middle of the remnant beam at 93 cm from the focus. The curved plywood construction allowed performance of intra-oral X-ray examinations of study participants and measurements of remnant beam doses.

and reported the mean dose [kerma (Gy)] measured over an area with a radius of 28 mm. The shape of the curved plywood extension allowed the measuring area of the survey detector to be located directly in the middle of the remnant beam during patient exposures (Figures 1 and 2). The focus-to-detector distance was 93 cm. This distance was found to be optimal after an iterative process. It was neither too long compromising the steadiness of the X-ray device, nor was it too short to interfere with the maneuvering of the device when aiming for the intra-oral exposures. The 93 cm as such

Figure 2 Schematic representation of the experimental setting. A: focal spot of the X-ray generator. B: dosimeter in the centre of the remnant beam. C: curved plywood extension attached to the X-ray machine with the dosimeter mounted at point B.

has no influence on the outcome of the study because all measurements were corrected for the focus-to-detector distance.

The following data were recorded during intra-oral radiographic exposures: radiation dose in the remnant beam (μGy); type of exposure [bitewing (BW), incisor and canine (IC) periapical, premolar and molar (PM) periapical]; exposure side (left or right); exposure time (s); detector measurement time (s). This last measurement was done to be able to correctly compensate for background radiation as will be described later in this section.

Measurements were also performed without a patient present, in the setting as described above, to obtain a baseline value. This baseline value is needed to calculate the transmitted fraction during patient exposures. During exposures of patients however, a PSP is always located between the focus and the dosimeter. The attenuation of the PSP adds up to the attenuation of the patient and prevents calculation of the pure patient transmission. Therefore a PSP plate (format 5.7×7.6 cm) was covering the end of the X-ray tube during baseline measurements, in order to compensate for attenuation of this PSP during the patient measurements. The baseline value was calculated as the mean of five 1 s exposures.

To compensate all measurements for background radiation (BGR), the BGR rate was established by activating the survey detector for 5 min in the room where the experiment took place, without activating the X-ray generator. The measurement was divided by 300 s to obtain the BGR rate. The measurement time for each experimental baseline and clinical exposure was registered in seconds. The product of the measuring time and the BGR rate was subtracted from the measured dose from the X-ray device to obtain a net dose.

The measured net doses refer to exposures with different exposure times. To normalise the measurements to dose values per product of 1 s and 1 mA (per 1 mAs), each recorded measurement was divided by the product of the exposure time and the tube current (7 mA). The normalized value was expressed as a percentage of the baseline dose value/mAs to arrive at the percentage of transmission.

Statistical methods

The transmission of different types of exposures were compared. As there were multiple measurements per patient the mean transmission percentage per patient was calculated. To make comparisons between pairs of exposures within patients and between left and right, the Wilcoxon Signed Rank test was used. Differences between males and females and between age groups could only be tested for bitewings because of the limited number of patients. Differences were assessed by the Mann-Whitney U test and the Kruskal-Wallis test, respectively.

Table 3 Exposures of patients undergoing intra-oral radiography

<i>N</i> = 323			
Type	Posterior periapical <i>n</i> = 67	Anterior periapical <i>n</i> = 90	Bitewings <i>n</i> = 166
Side	Left: <i>n</i> = 159		Right: <i>n</i> = 164
Exposures per patient	Mean: 7.5 exposures		Range 2–24 exposures

Finally, a mixed model analysis was performed to assess the effects of “type of exposure”, “left or right side”, “gender” and “age” on the transmission percentage. This model takes the dependent observations within a patient into account. Statistical significance was assumed for $p < 0.05$.

A reference value for the transmission percentage of the remnant beam through the patient during intra-oral radiography was calculated. The reference value was obtained by adding the mean transmission value of the exposure type with the highest transmission percentage to twice the SD for that value. The sum was rounded up for convenience. Data was recorded into Microsoft Excel 2013 (Microsoft Ltd., Redmond, WA), and statistical analysis was performed by SPSS v. 21 (IBM Corp., New York, NY; formerly SPSS Inc., Chicago, IL).

Results

The output tests of the X-ray generator showed that the timer was accurate, and the tube voltage was consistently measured to be 0.5 kV lower than 60 kV. The dose at the end of the tube was 0.425 mGy/mAs (SD 0.019). The BGR in the room where the experiment took place was found to be 0.044 nGy/s. The correction for BGR of the measurement values was on average 0.04% (range 0.004–28%).

A total of 43 participants were included in the study. Demographic characteristics of the study population are shown in Table 2. Measurements were performed during 323 exposures. Details on the numbers and types of exposures are shown in Table 3.

The baseline measurement of the beam that was performed without a patient and through the PSP corrected for BGR was 20.65 µGy/mAs (SD 0.01).

Differences in the mean transmission percentages between IC and PM ($p < 0.01$) and between BW and IC ($p < 0.01$) were significant (Figure 3). The difference between left and right exposures when tested within

Table 2 Study participants

<i>N</i> = 43		
Gender	26 males	17 females
Age	Mean 46.1 years (SD 15.0)	Range 23.6–68.8 years

SD, standard deviation.

Gender and age of participants.

Figure 3 Boxplots of mean transmission percentages, averaged within patients over type of exposure. Mean value for BW was 1.78% (SD 1.15%), for IC periapical was 0.64% (SD 0.63%) and for PM periapical was 2.60% (SD 0.98%). The outlier values (patients #2 and #39) were defined as values exceeding the third quartile by 1.5-fold the interquartile range. BW, bitewing; IC, incisor and canine (IC); PM, premolar-molar; SD, standard deviation.

exposure types was not significant. Differences between males and females and between age groups were not significant.

In a mixed-model, with transmission percentage as the dependent value and patient as the random factor, no differences were found for left vs right, gender and age groups. The only significant factor was exposure type, which was consistent with univariate tests.

The highest mean transmission percentage for PM (2.60%) plus twice the SD (0.98%) was used as the reference value of 4.56% for the transmission percentage of the remnant beam through the patient during intra-oral radiography. For safety and convenience, the transmission reference value was rounded up to 5%.

Discussion

Assessment by an RPE of the ambient radiation dose in the dental office from intra-oral radiography requires quantification of the different contributing components. Leakage radiation and scattered radiation can be estimated based on the manufacturer's specifications and a conversion factor for the scattered radiation, which was described in a previous report from our research group.³ This present study obtained a transmission factor for the average patient, to be used to assess the dose from the remnant beam. With a known workload it is possible to make a safe estimation for the environmental dose. However, there are some factors to take into account when the remnant beam is assessed.

One factor to take into account for assessing the ambient dose is the direction of the exposures, which varies. For example, bitewing exposures are presumably

made with the same frequency on the left and right sides. Bitewing exposures are the most frequent exposures, with an almost 50% contribution to the total workload, as shown in our previous study.³ Therefore the highest dose, and thus the most critical area for the risk evaluation performed by the RPE will be found in the area of the remnant beam of the left and right bite-wing exposures.

Another factor is the attenuation by the image receptor. The current study was designed to obtain the transmission factor of only the patient, where the PSP plates used were taken out of the equation. Therefore, our results can be used for all types of image receptors. From our experiments, we know that attenuation by image receptors varies between approximately 50% for PSP to greater than 90% for digital sensors, with attenuation by conventional film somewhere in between. However, the area of the beam is larger than the area of the image receptor, and a portion of the beam therefore passes around the receptor and is attenuated only by the tissues of the patient before it exits as the remnant beam. Our transmission value is therefore a safe estimation because it was derived for the beam portion that misses the image receptor. The region behind the image receptor has a substantially lower remnant beam dose. A rectangular collimator used according to the guidelines will markedly reduce the dose of the remnant beam that misses the image receptor.

In this study, the measurements were performed for adult participants. Intra-oral radiography of children will likely result in greater beam transmission because of smaller dimensions of the soft and hard tissues in a child's head. The frequencies of exposure types were found to be different for children as well.³ The proportion of intra-oral exposures of adults and children that are bitewing exposures in our institution are approximately 50% and close to 80%, respectively. This difference should be taken into account for determining the ambient radiation dose in offices that predominantly treat children.

In our experiments we used a tube voltage of 60 kV for the patient exposures. This is a regular setting for intra-oral radiography; however, some equipment operates at a higher tube voltage, leading to a higher transmission percentage. Experiments performed at our department that used a radiological phantom found a 1.5-fold higher transmission for 70 kV in comparison to 60kV. This is consistent with the fact that higher-energy X-ray photons are less likely to interact with matter. A clinical study using a tube voltage of 70 kV should probably be performed to address this issue. As long as such a study is not performed the RPE assessing ambient dose for intra-oral radiography with 70kV should assume transmission through the patient of at least 1.5-fold the proposed transmission value for 60kV.

We found that anterior exposures resulted in significantly lower transmission. This is probably because the distance the X-ray beam travels through the tissues

Figure 4 Schematic representation of dose calculations. Starting point of the calculations is the dose at point A, the dose at the end of the tube (30.5 cm distance to focus), which was 0.425 mGy/mAs in the experiment reported in this paper. To assess the dose in the remnant beam at point B, the reduction of the dose by distance, using the inverse square law is applied, in this case reduction by a factor (30.52/40.52). Next the transmission factor of 5% is applied. This results in a dose 1.01 at point B of $\mu\text{Gy}/\text{mAs}$, which can be converted to 1.5 $\mu\text{Sv}/\text{mAs}$ using a conversion factor from air kerma to H^*10 . It should be taken into account that not the complete workload is directed towards point B. The scattered radiation dose at point C is quantified by the conversion factor introduced in part 1 of this series, which was 0.05 $\mu\text{Sv}/\text{mAs}$ at 1 m.²

of the patient is longer. Furthermore, the back of the skull and the cervical spine are bony structures through which the beam passes, and provide increased attenuation. In addition, the chair headrest, which contains metal components, was located between the X-ray focus and the dosimeter. The higher transmission values found in the posterior exposures were used to obtain our reference transmission percentage to provide a safe overestimation.

The remnant beam produced during intra-oral radiography contributes more to the ambient dose than scattered radiation. In part 1 of this study we proposed a reference value for scattered radiation of 0.05 $\mu\text{Sv}/\text{mAs}$ workload at 1 m at the level of the occlusal plane. If we compare this reference value to the remnant beam dose at 1 m from the patient, based on our data, this dose is 30-fold higher (Figure 4).

The remnant beam as measured in the current study also includes scattered radiation produced by the tissues of the patient as this was also registered by our detector. This led in fact to an overestimation of the remnant beam of 3.3% (given the factor 30 mentioned in the previous paragraph). We think it is convenient for the RPE to have this dose included in the remnant beam estimation by our transmission reference value. If this were not the case the RPE would be obliged to make

two separate calculations for remnant beam and add the scattered radiation dose level which is not practical and given the ratio between remnant beam and scattered radiation of 30:1 unnecessary cumbersome.

In contrast to our data, the data of the study by Richards *et al* show that the dose of the extension from a bitewing exposure of 65 kVp was 5-fold higher than the scattered radiation dose in front of a phantom.⁴ The higher difference found by us might be explained by the fact that the measurements by Richards *et al* were taken in the direction but not exactly at the height of the remnant beam.

De Haan and Van Aken performed measurements in the remnant beam from a bitewing exposure. The remnant beam in the rectangular area at 1 m from the head of the phantom showed a clearly higher dose than the surrounding area.⁶ The dose there was expressed as a fraction of the dose level at 30 cm from the focus (at the end of the tube). As commented upon in part 1 of this series, the doses reported in their study were

unrealistically high, being higher than expected from values obtained by the inverse square law.³

Intra-oral radiography performed with the patient in a supine position results in a remnant beam projecting in different directions. Kuroyanagi *et al* studied the dose around a supine phantom but did not measure the dose in the area of the remnant beam.⁹ However, the dose in the remnant beam from a supine patient undergoing intra-oral radiography should not differ from the dose in the remnant beam from a patient in the upright position.

In conclusion, for the remnant beam as a component of ambient radiation dose, this study derived a safe reference patient transmission factor of 5%, which is the value we advise for assessing the remnant beam from the average patient undergoing intra-oral radiography with a tube voltage of 60 kV. Anterior exposures result in significantly lower transmission than posterior exposures.

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