RESEARCH ARTICLE

The effects of device position on the operator's radiation dose when using a handheld portable X-ray device

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Introduction: Handheld X-ray devices are now offered in dental practice. Handheld X-ray units challenge the concept of a restricted access to the “controlled area” as they are held by the operator. Although an integral lead shield is provided, the distance from the body is variable, dependent on how the device is held. The aim of this article was to investigate the level of operator dose when using a handheld X-ray device in various positions.

Material and Methods: A NOMAD Pro™ Handheld X-ray system (Aribex Inc., Charlotte, NC) fitted with a remote control and mounted on a tripod was used in this study. A maxillofacial phantom ATOM® Max Dental and Diagnostic Phantom, model 711 HN (CIRS Inc., Norfolk, VA) was used to simulate the patient's head position. A mannequin was used to represent the operator. Pre-calibrated thermoluminescent dosimeters (TLDs) (Qados, Agar Scientific, Stansted, UK) were placed on the mannequin close to the eyes and at the level of thyroid, trunk, waist, hand (right finger + left palm) and feet, and three TLDs were used for background radiation. Three test scenarios were investigated; Position 1, close to operators' body and parallel to the ground; Position 2, away from the body with the arms fully extended (approximately 40 cm distance) and parallel to the ground; Position 3, perpendicular to the ground while the arms are partially extended. 30 exposures each of 1 s were performed in each test.

Results: Background radiation was measured at 0.0110 mGy. The highest exposure after subtracting background radiation was recorded on the palm of the left hand (0.0310 mGy) at Position 3. The estimated dose to the operator was calculated based on an average workload of 100 intraoral radiographs weekly for a dental practitioner working 46 weeks a year.

Conclusions: There is a negligible increase in operator exposure levels using handheld X-ray devices which remain well below the recommended levels of the Ionizing Radiation Regulations 1999. They could however represent an increase from what should be a nil exposure when using a wall-mounted machine. The position of the device relative to the operator has a significant effect on the overall operator's radiation exposure. The use of personal dosimeters is highly recommended to ensure a continuity of low radiation dose exposure. Furthermore, guidance, training and protocols on usage must be in place, strictly adhered to and regular audits are necessary to ensure compliance.

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Introduction

Dental radiographs are an integral part of everyday clinical dentistry. Dental X-ray equipment are commonly fixed (wall, floor or ceiling mounted) or mobile

(tripod mounted on a set of wheels). A fairly new concept is the handheld, battery operated, portable X-ray unit which has come on the market. In the past, the majority of handheld, portable X-ray units are modified machines, for use in military medicine, humanitarian missions and training exercises.^{1,2} They are also used in archaeological excavation sites, crime scene/disaster areas for forensic dentistry imaging and veterinary applications. The advantages of these devices extend to dental patients who are homebound or institutionalized with limited mobility and patients undergoing general anaesthesia,^{3–5} where conventional fixed or mobile X-ray units are not easily available.

In general, a handheld portable X-ray unit is designed to be used by holding the integral handle with outstretched hands, away from the body, parallel to the ground and activated at arm's length distance. The mode of use has raised a number of questions over possible radiation safety issues affecting the operator. Maintaining a safe distance, outside the "controlled zone", and not holding the X-ray equipment are universally recommended when using fixed or mobile X-ray units to avoid exposure from radiation leakage from the X-ray tube head and from backscatter.

The main concern with handheld portable X-ray units is unnecessary exposure to radiation and the dose to the operator. In the UK, it is a common practice to have a designated "controlled area" when using X-ray equipment. This is to prevent potential and unnecessary radiation exposure to the staff and general public. The "controlled area" is a zone 1.5 m in any direction from the patient and X-ray tube head and anywhere in the line of the main X-ray beam. Any radiation outside the "controlled area" is sufficiently attenuated by distance or shielding. In addition to this, the operator is required to be well outside the "controlled area", at least 2 m from the X-ray source.⁶

Handheld portable X-ray units challenge the concept of a restricted access to the "controlled area" as they are held by the operator. To overcome this problem, manufacturers have included a lead shield within the handheld portable X-ray unit. In addition, there is a lead-embedded acrylic protective shield at the end of the X-ray tube head, to create a protective zone against backscatter.

The available literature on handheld portable X-ray devices showed that the amount of radiation experienced by the patient and operator are below the recommended dose when the effective dose is calculated directly.^{3,7–11} However, the distance away from the body is variable, dependent on the position of the hands and how the portable X-ray device is held by the operator. In addition, the only integral protection for the operator is a backscatter shield. Hence, it remains questionable whether these measures are sufficient to prevent unnecessary radiation exposure to the entire operator's body. For this reason, occupational dose monitoring is often recommended for these operators. Therefore, the aim of this article was to investigate the equivalent doses to likely exposed parts of the operator and doses indicative

of occupationally recorded effective doses when working in various positions and postures using a handheld portable X-ray device.

Methods and materials

A NOMAD Pro™ Handheld X-ray system (Aribex Inc., Charlotte, NC) fitted with a remote control and mounted on a tripod was used in this study. The NOMAD Pro was set at 60 kV, 2.3 mA, according to the manufacturer's instructions; it has a focal spot of 0.4 mm and focus-to-skin distance of 20 cm. The protective lead-embedded acrylic backscatter protective shield was placed at the most anterior position of the X-ray tube head.

A maxillofacial phantom ATOM® Max Dental and Diagnostic Phantom, model 711 HN (CIRS Inc., Norfolk, VA) was used to simulate the patient's head position. A mannequin, overall height 1.82 m, was used to represent the operator. All tests were performed on an operating table of a fluoroscopic unit within the main radiology department of The Royal London Hospital, London, UK. The remote control unit allowed it to be used behind a protective lead screen to ensure that the unit was used from outside the "controlled area", and no personnel was exposed to radiation during this study. Before commencing the study, the assembly was tested for radiation safety to confirm that the equipment was working within specifications and that the radiation protection measures used were adequate.

To measure the equivalent doses to the operator's body and to estimate the effective doses as recorded by an occupational dosimeter, pre-calibrated thermoluminescent dosimeters (TLDs) (Type TLD 100H from Qados; Agar Scientific, Stansted, UK) were placed on the mannequin close to the eyes and at the level of the thyroid, trunk, waist, hand (right finger + left palm) and feet (Figure 1), and three TLDs were used for background radiation. These areas were identified as either likely to be insufficiently protected by the inbuilt scatter shield (eyes, thyroid, hands, feet) or were chosen to give an indication of effective dose as measured by conventional occupational dose badges (trunk, waist). Owing to the design of the mannequin, the eye TLD had to be placed on the forehead—this does not significantly change the dose recorded, but inverse square law correction indicates a –3% difference in radiation intensity at this point. This small variation is not considered in the analysis.

The TLDs are sensitive to small quantities of radiation down to 0.0001 mGy, and measurement errors are significantly reduced when measuring larger quantities of radiation. The background radiation was assessed using an average reading from three unexposed TLDs from the same batch as those used in the experiments. In each experiment, three TLDs were exposed in each measurement position to 30 exposures of 1 s each. The average TLD reading at each position (after background subtraction) was then noted. This ensures that the measured radiation level is well above the minimum

Figure 1 Demonstrating the positions of the thermoluminescent dosimeters on the mannequin (a) head, (b) neck and trunk, (c) left finger, (d) right palm, (e) waist and (f) feet.

dose threshold of the TLDs, the background subtraction is not a significant source of error and any measurement errors due to variation in TLD performance are averaged out so as to become insignificant.

As for the acquisition positions of the operator, three test scenarios were investigated; the handheld portable X-ray device:

- (1) close to operators' body and parallel to the ground
- (2) away from the body with the arms fully extended (approximately 40 cm distance) and parallel to the ground
- (3) perpendicular to the ground while the arms are partially extended.

The first two positions simulate the patient's position seated, whereas the third position lying down on a dental chair (Figure 2). After each test, new unexposed TLDs were placed on the mannequin for the next measurement.

Results

Average background radiation was measured with an independent set of TLDs for the purpose of this experiment at 0.0110 mGy. The background radiation was then subtracted from the dose registered on the TLDs.

These numbers were then entered into a formula to reflect the average workload of a dental practitioner of 46 weeks a year at no more of 100 intraoral radiographs per week. These values appear in Tables 1, 2 and 3.

$$\begin{aligned} & \text{Registered dose} \\ & 200 \text{ (based on 30 exposures of 1 s each which is 200 dental exposures at 0.15 s)} \\ & \times 4600 \text{ (46 weeks at 100 intraoral per week workload)} \end{aligned}$$

There was no additional exposure recorded to the lens, trunk and waist in Test 2. The exposure values were ≤ 0 for trunk and foot in Test 1 and Test 3, respectively.

In relation to the thyroid gland, the highest exposure recorded was for Test 1 (0.0043 mGy) but decreased subsequently with Test 2 (0.0023 mGy) and Test 3 (0.0013 mGy). The forefinger of the right hand (the representative trigger finger) recorded a similar exposure for Test 1 (0.0120 mGy) and Test 2 (0.0117 mGy) but a lower exposure for Test 3 (0.0070 mGy). The palm of the left hand recorded a variable amount of exposure in all the tests; the highest exposure recorded was in Test 3 (0.0310 mGy). Exposure to the waist was greater in Test 3 (0.0110 mGy) followed by Test 1 (0.0057 mGy). The foot recorded 0.0047 mGy and 0.0030 mGy in Test 1 and Test 2, respectively.

Figure 2 Operator acquisition positions. (a) Test 1: device close to operator's body and parallel to the ground. (b) Test 2: device away from the body with the arms fully extended (approximately 40 cm distance) and parallel to the ground. (c) Test 3: device perpendicular to the ground while the arms are partly extended.

Discussion

Previous publications have shown that the radiation dose from using the NOMAD handheld X-ray unit is below the recommended annual dose limit. However, most of the studies were performed in the USA^{1,2,4,7–14} with only a few studies in other countries, for example, Italy,⁵ Belgium^{3,15} and Korea.¹⁶ To date, there are no reports from the UK although the device is available in the country.

The regulations and the recommended radiation exposure dose limits are not the same worldwide. In the UK, the Ionizing Radiation Regulations 1999 suggests an annual whole-body effective dose constraint of 0.3 mSv for the general public and 1 mSv for the operator, who is directly engaged with dental radiography.⁶ Public Health England has calculated that, on average, the public is exposed to about 2.7 mSv of radiation a year.¹⁷ The annual dose limits for non-classified workers, which include dentists and radiographers, are 6-mSv whole-body effective dose and 150-mSv equivalent dose to the extremities and eyes. To achieve these limits, the Dental guidance notes⁶ suggested that the controlled area to be:

- within 1.5 m from the X-ray source and patient in any direction
- within the primary X-ray beam, until it has been sufficiently attenuated by distance or shielding.

Table 1 Average thermoluminescent dosimeter-recorded radiation exposure with background radiation

Position	Exposure with background radiation		
	Test 1 (mGy)	Test 2 (mGy)	Test 3 (mGy)
Lens	0.0127	0.0110	0.0120
Thyroid gland	0.0153	0.0133	0.0123
Finger of right hand	0.0230	0.0227	0.0180
Palm of left hand	0.0203	0.0167	0.0420
Trunk	0.0107	0.0103	0.0123
Waist	0.0167	0.0107	0.0220
Foot	0.0157	0.0140	0.0110

Therefore, the preferred operator position is ≥ 2 m from the X-ray tube head and patient; well out of the direction of the primary beam or in a protected area (e.g. shielded partition) provided for the operator.⁶

The maximum permissive dose (MPD) for an occupational radiation worker in the USA is 50 mSv for whole body, 150 mSv for the eyes and 500 mSv for hands, skin and feet.¹⁸ The USA's National Commission for Radiation Protection and Measurements 2010 indicated that dental workers should not receive effective doses above 1 mSv per year.¹⁹

Given the limited literature available to support its unquestioned usage and the shift in the concept of needing access to a "controlled area", there is continuing and understandable concern and anxiety about the radiation safety of handheld portable X-ray devices. In this study, the maximum radiation dose recorded was for the left palm when the device was held perpendicular to the ground with the arms extended. Another study looked into this issue was by Danforth et al⁷ in which the exposure to operator in typical (when the operator is in an upright position imaging a patient who is seated) and atypical positions (when the operator was in an upright position imaging a patient in the supine position) were investigated; they found that the reproductive organs received the highest dose, whereas the thyroid glands received the lowest dose. The study also found that the operator's backscatter exposure was $<1\%$ of annual occupational MPD, and it was dependent on the operator position.⁷ The operator exposure whole-body dose was 0.0453 mSv per year, which is equivalent to 0.9% of the annual MPD. The highest exposure recorded was to the reproductive organs, 0.095 mSv per year (0.19% of MPD).⁷

A number of previous studies had shown the importance of the backscatter shield and significant reduction in the operator dose when the backscatter shield was used. McGiff et al⁸ compared the operator's dose, with and without the presence of the backscatter shield; the radiation dose to the operator's head/torso/extremities with the backscatter shield was <0.6 mSv per year,

Table 2 Average thermoluminescent dosimeter-recorded radiation exposure after subtracting the background radiation of 0.0110 mGy

Position	Exposure after subtracting the background radiation		
	Test 1 (mGy)	Test 2 (mGy)	Test 3 (mGy)
Lens	0.0017	0.0000	0.0010
Thyroid gland	0.0043	0.0023	0.0013
Finger of right hand	0.0120	0.0117	0.0070
Palm of left hand	0.0093	0.0057	0.0310
Trunk	≤0	≤0	0.0013
Waist	0.0057	≤0	0.0110
Foot	0.0047	0.0030	0.0000

whereas without the backscatter shield, it was 2 mSv per year. Hermesen *et al*⁹ (2008) also noted that the radiation dose was almost ten times higher without the backscatter shield. Cho *et al*²⁰ checked radiation dose to the operator at hand, chest and waist levels when using a portable X-ray device (DX3000, Dexcowin Co Ltd., Seoul, Korea). They reported that the backscatter shield reduced the dose to 23–32% at hand level; the operator dose was reduced to 0.1% at chest level and to 37% at waist level.²⁰

Goren *et al*¹⁴ carried out dosage measurement to assess the possible leakage of radiation and backscatter radiation through the protective lead-filled acrylic shield, the patient exposure and image quality. It was concluded that the risk to the patient and operator from the NOMAD handheld X-ray device was no greater than conventional dental X-ray generating equipment and was well below the recommended levels. In a later study, Goren *et al*¹² tested the radiation leakage, backscatter radiation through the acrylic shield, exposure to patient and operator; the estimated annual dose was 18 mR per year to the operator's chest, 22.5 mR per year to the eyes and 45 mR per year to the finger.

Hermesen *et al*⁹ reported a maximum scatter radiation dose of 0.253 mSv from the NOMAD handheld portable X-ray unit when used by forensic dental personnel who were deployed in disaster prone areas for 2 weeks and 0.506 mSv for those who were deployed for 4 weeks. The leakage and scatter radiation dose from NOMAD handheld portable X-ray unit were well below the established radiation safety guidelines of 50 mSv per year.

Gray *et al* collected 661 personnel radiation dose records of dental staff from 18 dental facilities. The radiation dose records included those for both handheld and wall-mounted X-ray units for film and digital imaging.¹⁰ The results demonstrated statistically significant differences in their doses; those for the NOMAD handheld device showed average monthly dose of 0.28 mSv compared with 7.86 mSv for wall-mounted units. Gray *et al*¹⁰ also suggested that using additional shielding, such as lead aprons, will not provide significant benefit or reduce the staff radiation dose. Unfortunately, these radiation doses were acquired by comparing the non-zero dose; the study did not specify the location of the operator when using the exposure wall-mounted

systems. It is important to note that the radiation exposure should be zero or negligible if the operators were behind the lead shielding or 2 m away from the X-ray source.⁶ Secondly, it is also important to ensure that the dose monitors were not exposed by other radiation sources, *e.g.* sunlight or background radiation. The duration for which the dosimeters were used has also not been taken into account, which may play a role in excessive doses recorded with the wall-mounted systems. In addition, the study did not highlight the dose from 116 finger dosimeters, which averaged 208 mSv per month with a mean of 23.5 mSv; the average monthly non-zero dose for all staff with the NOMAD handheld device was 9.01 mSv compared with 27.3 mSv for wall-mounted systems.¹⁰

Cho and Han²⁰ also raised the issue of machines available in the Korean market without protective shields. Previous incidence of using cheap handheld portable X-ray devices by dentists in the UK has resulted in exposing users to unacceptable levels of radiation. It is important to note that manufacturers of handheld portable X-ray devices must comply with the requirements of the relevant regulatory bodies.^{21,22}

Other recommendations from Cho *et al*²⁰ are the use of lead gloves, which have been shown to reduce the operator radiation exposure dose by 26–31%.

Pittayapat *et al*³ (2010) assessed the image quality between a wall-mounted and portable dental X-ray unit. In this study, it was also demonstrated that the radiation dose to the operator's hand when using the NOMAD handheld device and protective shielding was 0.1 mGy.³ The literature from the manufacturer of NOMAD indicated an annual dose of 0.30 mSv and 0.12 mSv for D- and F-speed films, respectively. The dose for digital sensors was also 0.13 mSv per year; this was the normalized average for 7200 exposures per year.²³

There was a recorded difference when the direction of main beam changed from parallel to perpendicular to the ground. This was particularly true for the left palm and the waist. The results lend support to the importance of adherence to the manufacturer's description of the zone of significant occupancy.²⁴

Table 3 Radiation exposure calculated after subtracting the background radiation for a workload of 100 intraoral radiographs per week in a year (46 weeks) (6 weeks of holidays)

Position	Exposure at a workload of 100 intraoral radiographs per week working for 46 weeks in a year		
	Test 1 (mGy)	Test 2 (mGy)	Test 3 (mGy)
Lens	0.0391	≤0	0.023
Thyroid gland	0.0989	0.0529	0.0299
Finger of right hand	0.276	0.2691	0.161
Palm of left hand	0.2139	0.1311	0.0310
Trunk	≤0	≤0	0.713
Waist	0.1311	≤0	0.253
Foot	0.1081	0.069	≤0

Format: Registered dose ÷ 200 (based on 30 exposure of 1 s each which is 200 dental exposures at 0.15 s) × 4600 (46 weeks at 100 intraoral per week workload).

The doses recorded in this study are expressed as absorbed doses to the surface of the body and are not used to deliver an effective dose as has been quoted by many of the works mentioned above such as the study by Danforth *et al*, McGiff *et al* or Gray *et al*. The value of effective doses in highlighting a corresponding numerical risk of cancer to the whole body is extremely valuable; however, for an X-ray unit in close proximity to the body, where the radiation source has the potential to irradiate the body non-uniformly, the use of effective dose does not describe the dose distribution across the body so will underestimate the overall radiation dose away from the torso. Our method provides this additional dose distribution information and is therefore useful in identifying risk to extremities, which is not available if a single figure effective dose is calculated.

Although the measured doses are well below the recommended levels by the Ionizing Radiation Regulations 1999 of 6 mSv for whole body and 150 mSv for extremities,²⁵ these figures from this study represents an increase from what would be 0 mSv effective and equivalent doses using a wall-mounted X-ray machine where the operator is positioned well outside the controlled area. This of course means that the attempt to keep exposure doses to the operator as low as reasonably practicable is not met. This is likely to be highlighted during the conduction of a risk assessment by the Radiation Protection Advisor.

The position of the handheld X-ray device relative to the operator has a significant effect on the overall radiation exposure received by the operator; this is, ultimately, determined by positional deviation from the area of significant occupancy as described by the manufacturer. The variation in the level of radiation exposure to various parts of the body of the operator is influenced by the positioning of the device and the direction of the main beam. This variation is only one of the multiple factors that could alter the distance of the device from the operator; the angle and the direction of the beam and the area covered by the anti-scatter grid are other factors. The purpose of the anti-scatter grid is to create a safety zone where the operator

is protected from scattered radiation. However, the shape and size of this safety zone would vary depending on the operator's height, arms' length (distance of the device from the operator) and the angle at which the device is aimed, which dictates the direction of the main beam and consequently the amount of the scattered radiation.

Handheld portable X-ray devices are clearly useful and have many advantages. They can be cost-effective especially in dental practices where there is more than one surgery. Selecting and using handheld portable X-ray devices which comply with relevant regulatory bodies is a must.

In conclusion, there is a negligible increase in operator exposure levels using handheld X-ray devices which remain well below the recommended levels of operators' exposure. However, handheld X-ray machines should not automatically replace wall-mounted machines in a dental practice as they are consistent with a recorded dose to some parts of the body which otherwise should be nil. They do, however, remain extremely useful in other environments such as domiciliary visits, surgical theatres and forensic dentistry.

The position of the handheld X-ray device relative to the operator has a significant effect on the overall radiation exposure received by the operator. It is essential to utilize them in such a fashion so the operator is positioned within the protective area created by the anti-scatter shield. The use of personal dosimeters is highly recommended, to ensure a continuity of low radiation dose exposure. Furthermore, guidance, training and protocols on usage must be in place, strictly adhered to and regular audits are necessary to ensure compliance.

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