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COMPARISON OF OPERATOR EXPOSURE DOSE IN PORTABLE INTRAORAL X-RAY DEVICES AND DOSE MANAGEMENT

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Abstract: *Objectives.* Portable intraoral X-ray devices were widely used for personal identification following the Great East Japan Earthquake. Although various models have been developed and are commercially available, few studies have compared their characteristics. As portable intraoral X-ray devices are often hand-held during use, it is important to understand the dose to the operator and to undertake dose management.

Methods. Fourteen types of portable intraoral X-ray device were compared. Semiconductor detectors were used to measure the output characteristics, using a cylindrical head phantom for computed tomography dose measurement as the object. An ionization chamber dosimeter was used to measure the dose distribution in air, with measurement points placed at radii of 0.5 m and 1.0 m from the center of the phantom. Measurements were taken over 360° at intervals of 15° with the primary X-ray beam at 0°.

Results. For all 14 devices, the average dose ± standard deviation was 0.243 ± 0.175 μSv per 1 mGy of cone-tip air kerma at 120° to 240° at a radius of 0.5 m. This value equates to approximately 200 intraoral radiographs per day at 2 mGy per radiograph, which exceeds the annual occupational exposure limit for operators.

Conclusions. Whenever there is risk of exceeding the dose limit, a plan for the task of identification must be formulated considering radiation protection.

Keywords: portable intraoral X-ray device, personal identification, operator exposure dose, dose management.

INTRODUCTION

The value of intraoral radiographs is well known for obtaining identifying information via dental records [1,2]. After the power supply was lost following the Great East Japan Earthquake, portable intraoral X-ray devices driven by secondary batteries or storage batteries were highly effective for performing dental personal identification [3-7]. In addition to their successful application in this disaster, due to Japan's super-aging society, a large number of such devices have been manufactured and sold in recent years to meet the demand for portable intraoral X-ray devices suitable for use in the community [8]. Although various devices are in current use, few studies have conducted a systematic comparison of their characteristics [9-11].

Hand-held units are the most common portable device used to obtain intraoral X-rays for dental personal identification. The operator positions the device close to the corpse under examination and the irradiation occurs while holding the device [12,13]. It is important to manage the exposure dose to the operator in close proximity to the subject because each irradiation generates scattered radiation, as well as any leaked radiation from the device [14,15]. In addition, it can be difficult to secure a sufficiently large distance between the subject and other personnel when dental personal identification is performed in a large-scale disaster. In such a situation, general workers doing other work in the vicinity are considered as members of the public for the purpose of radiation protection, and are also at risk of exposure. However, there are few

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reports regarding radiation protection for operators of portable intraoral X-ray devices or for members of the public who are at risk [16,17].

Therefore, in this study, we used a uniform method to measure the specifications and exposure doses for a range of portable intraoral X-ray devices currently in wide use in Japan. For each model, we compared stray radiation dose (including scattered radiation, leaked radiation, and primary radiation) and calculated exposure doses to operators and to the public. The purpose of this study was to evaluate various portable intraoral X-ray devices and assess the radiation safety of operators and the public during irradiation for dental personal identification.

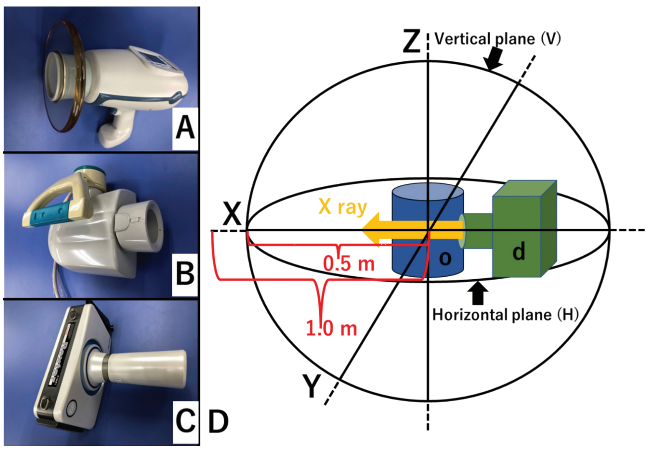

Figure 1. Examples of portable intraoral X-ray devices and diagram of measurement geometry. A: NOMAD Pro, B: Dentnavi Hands, and C: REXTAR S devices. D: The arrangement for measurement of air dose distribution at radii of 0.5 m and 1.0 m (o: object phantom, d: X-ray device, H: XY plane, V: XZ plane).

MATERIALS AND METHODS

Materials

We tested the following 14 portable intraoral X-ray devices, all of which are currently available: Dentnavi Hands (YOSHIDA DENTAL MFG. CO., LTD, Tokyo, Japan), Dexco ADX4000W (DEXCOWIN CO., LTD, Seoul, Korea), Dexco DX3000 (DEXCOWIN CO., LTD), KX-III (ASAHI-ROENTGEN IND. CO., LTD, Kyoto, Japan), KX-IIICL (ASAHI-ROENTGEN IND. CO. LTD), KX-60 (ASAHI-ROENTGEN IND. CO., LTD), KX-60CL (ASAHI-ROENTGEN IND. CO., LTD), Move Ray (iCAT CO., LTD, Osaka, Japan), Naomi Portable DX (RF CO., LTD, Nagano, Japan), NOMAD (IDENS CO., LTD, Osaka, Japan), NOMAD Pro (IDENS CO., LTD), PORT X-III (J. MORITA CO., LTD, Tokyo, Japan), REXTAR S (KINKI-ROENTGEN IND. CO., LTD, Tokyo, Japan) and X-shot (YOSHIDA DENTAL MFG. CO., LTD, Tokyo, Japan). Three representative models are shown in Figure 1A–C. The specifications for each model (tube voltage, tube current, total filtration (TF), cone-tip diameter, focal spot-to-object distance (FOD), X-ray tube type, and focal spot size) are shown in Part I of Table 1. An international electrotechnical commission (IEC)

Table 1. Device specifications (Part I) and measured values (Part II)

	Part I: Device specifications							Part II: Measured values			
Model	**Tube voltage (kV)**	**Tube current (mA)**	**TF (mm Al eq.)**	**X-ray field (mm)**	**FOD (cm)**	**X-ray tube***	**X-ray focus (mm)**	**Tube voltage (kVp)**	**HVL (mm Al)**	**X-ray field (mm)**	**Cone-tip dose (mGy)**
Dentnavi Hands	60	4	-	φ54	20	B	0.7	57	1.9	54	4.15
	60	7						57	1.9	54	6.25
	70	4						67	2.2	54	5.56
	70	7						65	2.2	54	8.28
Dexco ADX4000W	60	2	1.5	φ60	≥15	A	0.8	61	1.9	60.3	3.98
Dexco DX3000	60	2	1.5	φ60	≥15	A	0.8	60	1.9	59.9	4.87
KX-III	60	2	1.5	φ60	15	A	0.8	60	2.0	59	3.81
KX-IIICL	60	2	1.5	φ60	20	A	0.8	60	2.0	59	2.15
KX-60	60	10	2.5	φ60	15	A	0.8	59	1.6	62	12.2
KX-60CL	60	10	2.5	-	15	A	0.8	60	2.2	-†	13.0
Move Ray	70	2	≥1.5	-	-	C	0.4	69	2.1	50	6.19
NAOMI Portable DX	60	2	1.6	-	-	A	0.8	65	1.9	73	3.25
NOMAD	60	2.3	≥1.5	φ60	20	D	0.4	62	1.9	63	4.03
NOMAD Pro	60	2.5	≥1.5	φ60	20	D	0.4	60	1.6	62	4.19
PORT X-III	60	2	1.8	φ60	20	A	0.8	58	1.9	61	2.42
REXTAR S	70	2	1.5	-	-	C	0.4	67	1.9	54	3.35
X-shot	60	2	≥1.5	-	-	C	0.4	62	2.1	55	1.81

TF, total filtration; FOD, focal spot-to-object distance; HVL, aluminum half-value layer. *X-ray tube: A, D-081B (Toshiba); B, D-0711SB (Toshiba); C, D-041 (Toshiba); D, VTD70/0.4/12CP (Vista Technology). †Model without cone.

standard computed tomography dosimetry head phantom (PMMA cylinder phantom, diameter 16 cm × height 15 cm; QualitA CO., LTD, Nagano, Japan) was used as the object. A Pitman 37D dosimeter with an attached 350 cc ionization chamber (Pitman CO., LTD, Weybridge, UK) was used to measure the air dose distribution (i.e., stray radiation) around the phantom. ThinX Rad semiconductor detectors (RaySafe CO., LTD, Uggledalsvägen, Sweden) were used in most cases to measure output characteristics such as cone-tip air kerma, sometimes in combination with Xi and X2 sensors (RaySafe CO., LTD). The X-ray field at the cone-tip was measured using HR-S (8 in × 10 in) film (Fujifilm CO., LTD, Tokyo, Japan).

Methods

A ThinX Rad (or Xi/X2) sensor was set at the cone-tip and the following output characteristics were measured during irradiation for 1.0 s (0.99 s for models without a 1.0 s setting): tube voltage (kVp), aluminum half-value layer (HVL) (mm Al), and cone-tip air kerma dose (mGy). To determine the X-ray field (mm), image diameter was measured on HR-S film set at the cone-tip and irradiated with a dose of 1.0 mGy.

The measurement geometry for air dose distribution (stray radiation dose) is shown in Figure 1D. The center of the phantom was set at a height of 1.0 m from the floor as the origin of the coordinate, and the central axis of the cylindrical phantom was matched vertically with the Z-axis of the coordinate system. The focal point of the X-ray device and the geometrical center of the ionization chamber were set at the same height. The cone-tip of the X-ray device was placed in contact with the surface of the phantom, and the primary X-ray was positioned toward the center of the phantom (origin). The XY plane perpendicular to the Z axis and parallel to the floor, passing through the origin, was defined as the horizontal plane, and the XZ plane perpendicular to the horizontal plane and passing through the origin was defined as the vertical plane. On these planes, a total of 24 measurement points were set up to 360° at intervals of 15° clockwise on each circumference for radii of 0.5 m and 1.0 m from the origin, with the primary X-ray beam set to 0°. For measurements in the vertical plane, both the phantom and the portable intraoral X-ray device were rotated 90° from the Z axis to the Y axis from the arrangement shown in Figure 1D, to bring the rotated XZ plane perpendicular to the floor. Measurements were then obtained in the same way as in the horizontal plane. We measured the stray radiation (irradiation dose in free air around the phantom) at these points during irradiation of 1.0 s, set at irradiation for 0.99 s for models that do not have a 1 s setting time (NOMAD Pro, KX-60, and KX-60CL). For the model with variable tube voltage and tube current (Dentnavi Hands), tube currents of 4 mA and 7 mA were selected at tube voltages of 60 kV and 70 kV, respectively. The Dexco ADX4000W and Dexco DX3000 models, which are equipped with an optional backscatter protection shield (S) at the cone-tip, and the NOMAD and NOMAD Pro models, which have a shield at the cone-tip, were measured with (S+) and without the shield (S–). A cone of length 20 cm was used for the Move Ray and REXTAR S models, for which a long or short cone can be selected. After confirming high reproducibility of the measured values, each point was measured once. However, as 0° and 360° are the same point, the average value was taken as the measured value for 0°. In addition, we confirmed that the influence of stray radiation from the direction of the floor can be ignored in this study. Stray radiation dose measurements were converted from R (or C/kg) units of exposure dose to μGy of air kerma using a conversion factor of 8.73 × 103 μGy/R. We normalized the μGy values to μGy/mGy by dividing by the cone-tip air kerma dose (mGy) at 1 s or 0.99 s exposure for each X-ray device. The region of interest (ROI) for operator exposure dose was the working space between the angles of 120° and 240°, and the ROI for public exposure and the control area was 0° (direction of the primary X-ray beam) assuming the worst case. Lateral spaces (15°–105° and 255°–345°) were evaluated as other ROIs.

RESULTS

Part II of Table 1 lists the radiation quality information of tube voltage and HVL as the output characteristics of the portable intraoral X-ray devices, and radiation field size and cone-tip aerial air kerma as the dose characteristics. For all 14 devices, the mean (average) ± standard deviation (SD) cone-tip dose was 5.26 ± 3.21 mGy. Tube voltage was generally within 10% of the nominal value. The average ± SD and other statistical measures (coefficient of variation/maximum/minimum/median) for all 14 devices were 61.7 ± 3.63 kVp (0.0589/69/57/60) and 1.95 ± 0.177 mm Al (0.0907/2.2/1.6/1.9), and beam quality was similar among the devices. Mean X-ray field was 58.4 ± 5.50 mm (0.0941/73/50/59.5).

Figure 2 shows the air dose distribution of stray radiation for all models in each of the horizontal and vertical planes at radii of 0.5 m and 1.0 m. Air dose distributions were similar for both planes except for 120°–240°. Table 2 lists the average ± SD and other measures (coefficient of variation/maximum/minimum/median) for all 14 models in the horizontal plane, vertical plane, and in the combined horizontal and vertical planes for each ROI (0°, 120°–240°, 15°–105°, and 255°–345°). The values at 120°–240° in the combined planes were 0.223 ± 0.161 μGy/mGy (0.724/0.727/0.00664/0.219) at 0.5 m and 0.0519 ± 0.0342 μGy/mGy (0.660/0.127/0.00354/0.0502) at 1.0 m, and the coefficient of variation was relatively large. At 0°, these values were 0.612 ± 0.117 μGy/mGy (0.191/0.856/0.317 /0.614) at 0.5 m and 0.205 ± 0.0476 μGy/mGy (0.232/0.306/0.111 /0.206) at 1.0 m, and the coefficient of variation was smaller anteriorly than posteriorly. In the combined ROIs (15°–105° and 255°–345°) at 0.5 m from the origin of the phantom, these values were 0.234 ± 0.0948 μGy/mGy (0.406/0.680/0.0797/0.210) and 0.0579 ± 0.0183 μGy/mGy (0.316/0.167/0.0230/0.0536), and the coefficient of variation was between the anterior and posterior values. In the combined horizontal and vertical planes at 0.5 m from the origin of the phantom, we divided the average values in each ROI for the total 14 models by 4, and the resultant values were 0.153 μGy/mGy at 0°, 0.0558 μGy/mGy at 120°–240°, and 0.0585 μGy/mGy in other areas. These values were within the standard deviation of the mean values of all models in the combined horizontal and vertical planes in each ROI at 1.0 m, and generally followed the inverse square law of distance.

DISCUSSION

The present evaluation of 14 portable intraoral X-ray devices found that the coefficient of variation for the air dose distribution of stray radiation was largest in the region of 120°–240° behind the device. We consider that the coefficient of variation was greatest in this region because of differences in shielding and absorption of backscattered and leaked X-rays among the various designs and structures of the portable intraoral X-ray

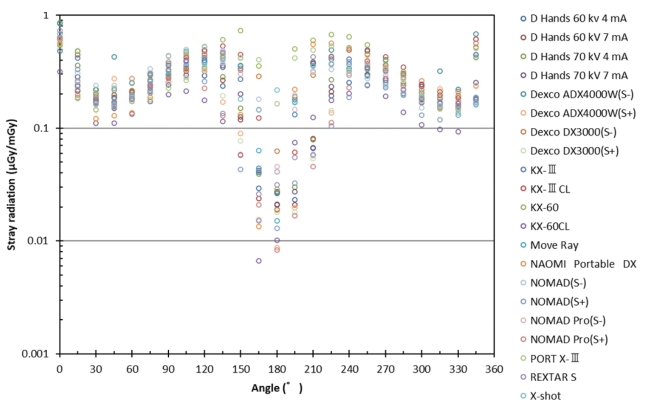

Figure 2.1. Stray radiation dose for each model in the horizontal plane at 0.5 m. D Hands, Dentnavi Hands; S+, with a backscatter shield; S−, without a backscatter shield.

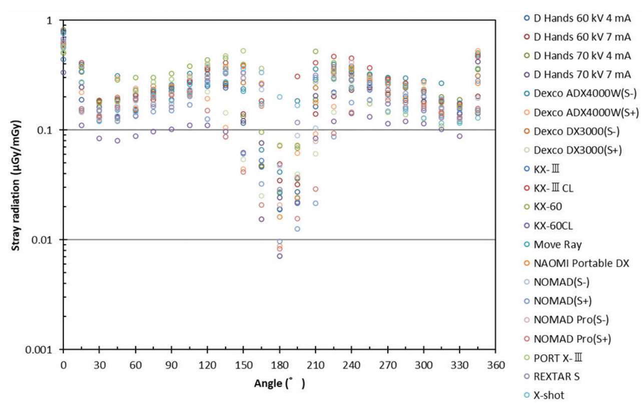

Figure 2.2. Stray radiation dose for each model in the vertical plane at 0.5 m. D Hands, Dentnavi Hands; S+, with a backscatter shield; S−, without a backscatter shield.

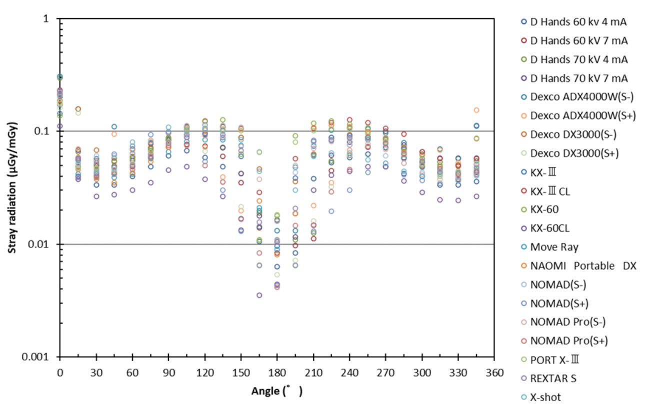

Figure 2.3. Stray radiation dose for each model in the horizontal plane at 1.0 m. D Hands, Dentnavi Hands; S+, with a backscatter shield; S−, without a backscatter shield.

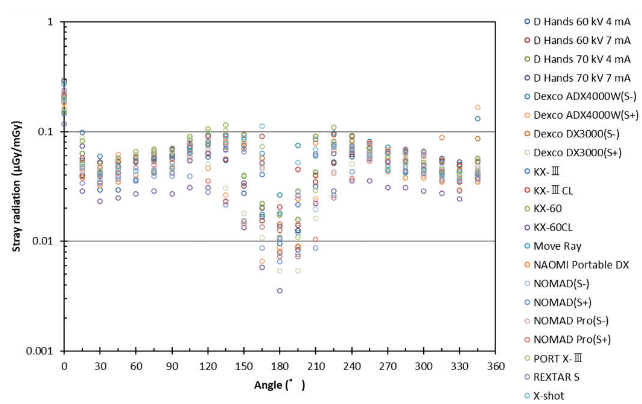

Figure 2.4. Stray radiation dose for each model in the vertical plane at 1.0 m. D Hands, Dentnavi Hands; S+, with a backscatter shield; S−, without a backscatter shield.

devices. In contrast, the coefficient of variation was the smallest and the average value was the largest at 0°, which is probably because the stray radiation dose, including primary X-rays and forward scattered radiation, was measured at 0° and the radiation quality and X-ray field did not differ significantly between models. As shown in Table 1, transmission of the X-ray spectrum and the scattered radiation volumes were also similar among the models. Furthermore, at 0°, scatter decreases with distance from the phantom center, and the primary X-ray beam is reduced according to the inverse square of the distance from the focal point. Therefore, it appears that the reduction rate is less than one quarter, similar to values for the combined horizontal and vertical planes in Table 2, because primary X-rays are included. As shown in Figure 2, the dose distributions were similar among devices but there was a significant difference (more than 10 times) between devices at 120°–240°, whereas the difference in dose distribution was approximately 2–3 times in other ROIs. This result is thought to be due to similarities in the primary X-ray beam spectrum, radiation quality, and X-ray field size among devices, and similar scattered X-rays generated, but considerable differences in shielding designs among the X-ray tubes in the portable intraoral X-ray devices. Accordingly, it is necessary to give due consideration to differences between the devices in terms of the stray radiation dose in the working area because this affects operator radiation safety.

In this study, we also considered safety management regarding portable intraoral X-ray devices. In Japan, it is stipulated that the occupational exposure of radiation workers should not exceed an effective dose of 100 mSv (20 mSv/year) in five years and should not exceed 50 mSv in any one year. If other workers are considered as members of the public, the limit of public exposure should not exceed 1 mSv/year (or 250 μSv/3 months) [18]. In addition, places where there is a risk of exceeding 1.3 mSv/3 months (1.3 × 4 mSv/year) must be designated as controlled areas and managed accordingly [19]. Assuming that 1 year is 52 weeks, 3 months is 13 weeks, and 1 week is 5 working days, then 1 year is 260 days, 3 months is 65 working days, and occupational exposure is 20 mSv/260 days = 76.9 μSv/day. As exposure to the public should not exceed 1 mSv/260 days = 3.85 μSv/day, places where the risk of exceeding 1.3 × 4 mSv/260 days = 20.0 μSv/day must be set as controlled areas. In the present study, we assumed an ROI of 120°–240° at 0.5 m for occupational exposure, an ROI of 0° at 1.0 m for public exposure, and an ROI of 0° at 2.0 m for controlled areas, and evaluated the mean value of stray radiation in both the horizontal and vertical planes. The measured values (Gy) were converted to Sv units by multiplying the 1 cm dose equivalent conversion factor (1.09 Sv/Gy) of external exposure to photon energy of 30 keV (aluminum half-value layer = ln 2/ 3.05 cm^{-1} = equivalent to 2.28 mm). We did not obtain measurements at 2.0 m because the values would be below the measurement limit of the dosimeter. The value at 2.0 m was calculated as 1/16 of the 0.5 m measurement at 0°, according to the inverse square law of distance. We assumed a cone tip dose of 2 mGy per intraoral radiograph, which is equivalent to that for a mandibular molar radiograph [20]. Table 3 shows the number of exposures to reach the dose limit per day for each model, the average value ± SD, and other statistical measures for all 14 models. The average value ± SD of the number of exposures for all 14 models per day to reach each prescribed dose was 200 ± 112 times for occupational exposure, 47 ± 12 times for

Table 2. Stray radiation in each plane according to region of interest for all 14 devices

Plane	Radius	Region of interest: 0°	120°–240°	15°–105°	255°–345°
Horizontal	0.5 m	0.624 ± 0.126 (0.202/0.856/0.317/0.620)	0.244 ± 0.179 (0.733/0.727/0.00664/0.227)	0.258 ± 0.0943 (0.366/0.498/0.111/0.235)	0.257 ± 0.115 (0.448/0.670/0.0974/0.267)
	1.0 m	0.207 ± 0.0514 (0.249/0.306/0.111/0.208)	0.0552 ± 0.0375 (0.680/0.127/0.00354/0.0541)	0.0659 ± 0.0245 (0.372/0.158/0.0266/0.0599)	0.0604 ± 0.0220 (0.364/0.127/0.0195/0.0631)
Vertical	0.5 m	0.600 ± 0.109 (0.182/0.824/0.334/0.587)	0.202 ± 0.139 (0.689/0.527/0.00709/0.203)	0.208 ± 0.0708 (0.340/0.409/0.0797/0.194)	0.211 ± 0.0814 (0.385/0.471/0.0866/0.230)
	1.0 m	0.203 ± 0.0447 (0.220/0.290/0.117/0.200)	0.0485 ± 0.0303 (0.625/0.115/0.00354/0.0476)	0.0525 ± 0.0140 (0.266/0.0981/0.0230/0.0527)	0.0530 ± 0.0174 (0.329/0.109/0.0250/0.0589)
Average of both planes	0.5 m	0.612 ± 0.117 (0.191/0.856/0.317/0.614)	0.223 ± 0.161 (0.724/0.727/0.00664/0.219)	0.234* ± 0.0948 (0.406/0.680/0.0797/0.210)	
	1.0 m	0.205 ± 0.0476 (0.232/0.306/0.111/0.206)	0.0519 ± 0.0342 (0.660/0.127/0.00354/0.0502)	0.0579* ± 0.0183 (0.316/0.167/0.0230/0.0536)	

*Average stray radiation at 15°–105° and 255°–345°. Data are presented as the mean ± standard deviation (μGy/mGy) (coefficient of variation/maximum/minimum/median).

controlled areas, and 48 ± 11 times for public exposure. Therefore, assuming 10 radiographs taken for each corpse, radiation protection measures such as wearing protective clothing are necessary because the annual dose limit for occupational exposure would be exceeded if 200 images of 20 corpses were taken. For 5 corpses (50 radiographs), the area 2.0 m or more away from the X-ray unit should be set as a controlled area, and it will be necessary to prevent personnel other than radiation workers from entering this area. Furthermore, the dose limit for public exposure would easily be exceeded even if X-rays are taken in only 5 corpses (50 radiographs), if members of the public are in the direction of the primary X-ray beam. Therefore, we consider that it is necessary to perform irradiation only after confirming that there are no personnel in the direction of the primary X-ray beam, even if only a small number of corpses are X-rayed. As shown in Table 1 and Figures 2.1, 2.2, 2.3, and 2.4, it is necessary to fully understand the dose characteristics of the device to be used and to formulate a plan for the task of identification because the cone-tip dose and the stray radiation dose vary considerably among models. As shown in Table 3, occupational exposure was reduced by approximately one-third in the Dexco ADX4000W, Dexco DX3000, NOMAD, and NOMAD Pro models when the shield was attached near the cone-tip compared with when the shield was not attached. Due to the remarkable effectiveness of the shield, models equipped with such a shield should be used if at all possible [14,21]. The trial calculations of differences between the models evaluated in the present study and shown in Table 3 could be used in drafting a plan for the task of identification.

In conclusion, for the 14 models evaluated in this study, the mean value ± SD of stray radiation at 120°–240° related to operator exposure dose was 0.223 ± 0.161 μGy/mGy (0.243 ± 0.175 μSv/mGy) at 0.5 m. The coefficient of variation was largest in this region, probably due to differences in shielding of scattered radiation and stray radiation, which varied according the structure and shape of the different models. In addition, for radiation safety when using a portable

Table 3. Number of exposures per dose limit for each device and statistical measures for all 14 devices

Model		Periapical radiographs per day (n) **76.9** μSv* at 0.5 m	**20.0** μSv† at 1.0 m	**3.85** μSv‡ at 2.0 m
Dentnavi Hands	60 kV 4 mA	247	44	47
	60 kV 7 mA	233	42	46
	70 kV 4 mA	200	31	34
	70 kV 7 mA	191	31	35
Dexco ADX4000W	Without shield	119	50	48
	With shield	296	52	48
Dexco DX3000	Without shield	122	53	51
	With shield	298	57	55
KX-III		144	63	61
KX-IIICL		105	41	46
KX-60		86	64	53
KX-60CL		395	80	87
Move Ray		143	32	35
NAOMI Portable DX		123	46	49
NOMAD	Without shield	133	44	43
	With shield	435	42	44
NOMAD Pro	Without shield	145	42	45
	With shield	442	44	45
PORT X-III		97	48	50
REXTAR S		129	39	40
X-shot		126	47	45
Average ± SD# (n = 14)		200 ± 112	47 ± 12	48 ± 11
CV		0.56	0.26	0.23
Max		442	80	87
Min		86	31	34
Median		144	44	46

*Annual limit of effective dose for occupational exposure is 20 mSv per year, equal to 76.9 μSv per day. †Annual limit of effective dose for public exposure is 1 mSv per year, equal to 3.85 μSv per day. ‡The control area must be set above effective dose of 1.3 mSv per 3 months, equal to 20.0 μSv per day. #Average number of exposures ± standard deviation (SD). CV, coefficient of variation; Max, maximum value; Min, minimum value.

intraoral X-ray device, radiation protection is necessary when taking more than 200 intraoral radiographs per day.

Conflict of interest

The authors declare that they have no conflict of interest.

Ethics statement

Only phantoms were used in the present study, so the need for informed consent or ethics approval was not necessary.

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