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Conversion coefficients for the estimation of effective dose in cone-beam CT

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ABSTRACT

Purpose: To determine the conversion coefficients (CCs) from the dose-area product (DAP) value to effective dose in cone-beam CT.

Materials and Methods: A CBCT scanner with four fields of view (FOV) was used. Using two exposure settings of the adult standard and low dose exposure, DAP values were measured with a DAP meter in C mode (200 mm × 179 mm), P mode (154 mm × 154 mm), I mode (102 mm × 102 mm), and D mode (51 mm × 51 mm). The effective doses were also investigated at each mode using an adult male head and neck phantom and thermoluminescent chips. Linear regressive analysis of the DAP and effective dose values was used to calculate the CCs for each CBCT examination.

Results: For the C mode, the P mode at the maxilla, and the P mode at the mandible, the CCs were 0.049 μSv/mGycm^2, 0.067 μSv/mGycm^2, and 0.064 μSv/mGycm^2, respectively. For the I mode, the CCs at the maxilla and mandible were 0.076 μSv/mGycm^2 and 0.095 μSv/mGycm^2, respectively. For the D mode at the maxillary incisors, molars, and mandibular molars, the CCs were 0.038 μSv/mGycm^2, 0.041 μSv/mGycm^2, and 0.146 μSv/mGycm^2, respectively.

Conclusion: The CCs in one CBCT device with fixed 80 kV ranged from 0.038 μSv/mGycm^2 to 0.146 μSv/mGycm^2 according to the imaging modes and irradiated region and were highest for the D mode at the mandibular molar. (***Imaging Sci Dent 2014; 44 : 21-9***)

KEY WORDS: Radiation Dosage; Radiography, Dental; Cone-Beam Computed Tomography; Effective Dose

Introduction

Cone-beam computed tomography (CBCT) which provides three-dimensional (3D) images, was developed for the dental use in the late 1990s.[1] The advantages of CBCT include a lower entrance dose, higher resolution, and lower cost than conventional computed tomography (CT). Moreover, CBCT provides 3D information via multiplanar and 3D reconstructed images. For this reason, its use in dental practice has rapidly increased and is commonly used in preoperative implant planning, the localization of impacted teeth, the diagnostic and surgical planning of oral and maxillofacial radiology, the evaluation of periodontal and periapical lesions, endodontic problems, and orthodontic treatment planning.[2-5] Although the dose of CBCT is lower than that of conventional CT, it is higher than that of conventional radiography mainly used in dental practice. There have been numerous studies about effective doses of CBCT using thermoluminescent dosemeter (TLD) chips.[6-12] However, this estimation method using TLD chips is laborious and time-consuming.

The establishment of diagnostic reference levels in medical imaging was recommended by the International Commission on Radiation Protection (ICRP) to promote the optimization of patient radiation exposure.[13] In Korea, diagnostic reference levels for diagnostic radiology including dental radiographic procedures were reported by the Korea

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Food and Drug Administration.[14-17] Since the entrance surface dose (ESD) and dose-area product (DAP) are well-defined and easy-to-use methods, they have been frequently used as the adequate dose quantities for DRLs.[18,19] Especially, DAP was recommended as a dose quantity for CBCT by Health Protection Agency (HPA) in the United Kingdom.[20] Lofthag-Hansen et al[21] compared two methods of the CT dose index (CTDI) and DAP to calculate the effective dose of CBCT examination, and they proposed that the DAP measurement was the appropriate method to determine the effective dose. In addition, they commented that the conversion factors should be determined according to the dental regions and radiographic techniques.[21]

In diagnostic medical radiology, the conversion factors from DAP to effective dose have been suggested by a number of authors.[22-24] There has been a very few reports about those in dental radiology. Looe et al[25,26] suggested the conversion coefficients for the estimation of effective dose of the intraoral, panoramic, and lateral cephalometric radiography. However, the conversion coefficient for CBCT remains unknown.

The objectives of this study were to measure the DAP and effective dose in one CBCT device and to determine the conversion coefficients from the DAP value to effective dose.

Materials and Methods

The Alphard VEGA (Asahi Roentgen Ind. Co., Kyoto, Japan) CBCT scanner, which has four fields of view (FOVs) including the C mode (200 mm × 179 mm), P mode (154 mm × 154 mm), I mode (102 mm × 102 mm), and D mode (51 mm × 51 mm), was used in this study.

The DAP was measured using the DIAMENTOR M4-KDK (PTW, Freiburg, Germany) (Fig. 1). In addition, the effective dose was measured using TLD-100 LiF chips (1.8 × 1.8 × 0.035 inch; Harshaw Chemical Co., Solon, OH, USA) in an adult male Alderson Radiation Therapy phantom of the head and neck (Radiology Support Devices, Inc., Long Beach, CA, USA) (Fig. 2).

Measurement of the DAP

An ionization chamber of DAP meter was located on the tube side of the CBCT scanner (Fig. 3). The DAP value was measured with two different exposure settings (the standard adult and low-dose exposure setting) at the four FOVs. Table 1 shows the exposure parameters and specifications of the CBCT scanner used in this study. The tube voltage and exposure time were fixed at 80 kV for 17 seconds. The tube current, the only exposure para-

Fig. 1. DIAMENTOR M4-KDK (PTW, Freiburg, Germany) used for the measurement of DAP.

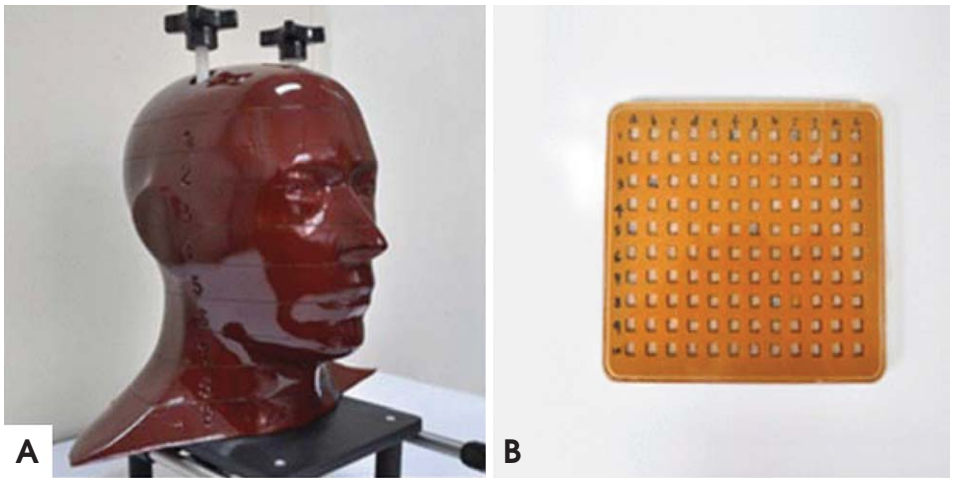

Fig. 2. Adult male ART head and neck phantom (A) and TLD-100 Li F chips (B) used for the measurement of effective dose.

Fig. 3. Ionization chamber of DAP meter is located at the tube side of CBCT machine for the measurement of DAP.

Table 1. Exposure parameters and specifications of Alphard VEGA CBCT

Mode (FOV; mm)	Exposure setting	Tube voltage (kV)	Tube current (mA)	Total filtration (mm Al)	Exposure time (sec)	Voxel size (mm)
C mode (200 × 179)	Adult	80	6	2.8	17	0.39
	Low dose	80	4	2.8	17	0.39
P mode (154 × 154)	Adult	80	9	2.8	17	0.3
	Low dose	80	5	2.8	17	0.3
I mode (102 × 102)	Adult	80	8	2.8	17	0.2
	Low dose	80	4	2.8	17	0.2
D mode (51 × 51)	Adult	80	9	2.8	17	0.1
	Low dose	80	6	2.8	17	0.1

meter selectable by the operator, was set at 6 mA for the adult exposure and 4 mA for the low dose exposure in C mode, 9 mA and 5 mA in P mode, 8 mA and 4 mA in I mode, and 9 and 6 mA in D mode. For the calculation of the conversion coefficients, the child exposure setting was considered the low-dose exposure in this study. All measurements were repeated three times and averaged for both exposure settings. The measured values were corrected by correction factors considering the temperature and air pressure during the DAP measurement.

Measurement of the patient effective dose

Location of TLD chips and CBCT image taking

The TLD chips were calibrated and annealed by the Iljin Radiation Engineering Company (Hwaseong, Republic of Korea). Twenty-two TLD chips were inserted in the adult male phantom and CBCT examinations were performed using the two different exposure settings. The CBCT examinations were done in the C mode, P mode (maxilla and mandible), I mode (maxilla and mandible), and D mode (maxillary incisors, maxillary molars, and mandibular molars) (Fig. 4).

Fig. 4. Adult male ART head and neck phantom is positioned for CBCT taking.

Measurement of the TLD chips and calculation of the effective dose

The effective dose was calculated using the method by Ludlow et al.[27] The TLD chips were used to record the absorbed dose at 22 locations in the head and neck of the phantom (Table 2). One TLD chip was placed in the thyroid gland, four in the salivary gland, eight in the bone marrow, one in the esophagus, four in the skin, two in the brain, four in the eye. Two chips in the lenses of eye were

Table 2. The locations of TLD chips in ART head and neck phantom

Phantom location	Phantom level	TLD ID
Calvarium posterior	1	1
Calvarium anterior	2	2
Calvarium left	2	3
Midbrain	2	4
Pituitary	3	5
Right orbit	3	6
Left orbit	3	7
Right lens of eye	3	8
Left lens of eye	3	9
Right cheek	5	10
Right parotid	6	11
Left parotid	6	12
Right ramus	6	13
Left ramus	6	14
Center cervical spine	6	15
Right mandible body	6	16
Left mandible body	6	17
Left back of neck	7	18
Right submandibular gland	7	19
Left submandibular gland	7	20
Midline thyroid	9	21
Esophagus	9	22

Table 3. Estimated fraction of tissue irradiated and the dosimeters used to provide an indication of dose to each organ

Organs/Tissue	Fraction indicated (%)	TLD ID
Bone marrow	16.5	
Mandible	1.3	13,14,16,17
Calvaria	11.8	1,2,3
Cervical spine	3.4	15
Thyroid	100	21
Oesophagus	10	22
Skin	5	8,9,10,18
Bone surface	16.5	
Mandible	1.3	13,14,16,17
Calvaria	11.8	1,2,3
Cervical spine	3.4	15
Salivary glands	100	
Parotid	100	11,12
Submandibular	100	19,20
Brain	100	4,5
Remainder		
Lymphatic nodes	5	11-17,19,20,22
Muscle	5	11-17,19,20,22
Extrathoracic tissue	100	6,7,11-17,19,20,22
Oral mucosa	100	11-14,16,17,19,20
Pituitary	100	5
Eyes	100	6,7,8,9

used to measure the dose in the eyes and skin. Only TLD chips that were calibrated within a 5% error were used in this experiment. For each examination, background radiation was also measured using five TLD chips that were not exposed to radiation. The measured background radiation was subtracted from the measured dose of each irradiated TLD chip. The tissue-absorbed doses (in μGy) at each anatomical site were calculated from irradiated TLDs readout. The products of these values and the percentage of a tissue or organ irradiated in a radiographic examination (Table 3) were used to calculate the equivalent dose (H_T) in μSv. Effective dose (E), expressed in μSv, was calculated using the equation: $E = \sum W_T \times H_T$, where E is the product of tissue weighting factor (W_T) and the equivalent dose (H_T). Table 4 shows the 2007 ICRP tissue-weighting factors.[28]

Table 4. Current International Commission on Radiological Protection (ICRP) tissue weighting factors (W_T)[28] for calculation of effective dose

Organs/tissue	2007 W_T
Gonads	0.08
Bone marrow (red)	0.12
Colon	0.12
Lung	0.12
Stomach	0.12
Bladder	0.04
Breast	0.12
Liver	0.04
Oesophagus	0.04
Thyroid	0.04
Skin	0.01
Bone surface	0.01
Brain	0.01
Salivary glands	0.01
Remainder	0.12*

*: adrenals, extrathoracic tissue, gall bladder, heart, kidneys, lymphatic nodes, muscle, oral mucosa, pancreas, prostate, small intestine, spleen, thymus and uterus/cervix

Table 5. The DAP values measured at different modes of Alphard VEGA CBCT

Mode (FOV; mm)	Exposure setting	kV	mA	DAP ($mGycm^2$)
C mode (200 × 179)	Adult	80	6	3704
	Low dose	80	4	2485
P mode (154 × 154)	Adult	80	9	4499
	Low dose	80	5	2508
I mode (102 × 102)	Adult	80	8	1910
	Low dose	80	4	956
D mode (51 × 51)	Adult	80	9	644
	Low dose	80	6	429

Determination of conversion coefficients

The measured DAP value and effective dose was in-

Table 6. Equivalent dose (μSv) at various organ and tissues exposed on the adult standard exposure setting according to the imaging modes

Organ/tissues	C mode	P mode		I mode		D mode		
		Maxilla	Mandible	Maxilla	Mandible	Maxillary incisor	Maxillary molar	Mandibular molar
Bone marrow	427.20	627.60	609.27	195.50	217.46	42.94	41.28	95.36
Oesophagus	27.77	44.55	35.70	17.11	43.39	2.56	5.95	17.36
Thyroid	533.06	919.01	821.49	403.31	871.90	99.17	104.13	315.70
Bone surface	1982.22	2912.07	2827.00	907.14	1009.02	199.25	191.54	442.46
Brain	1529.75	2554.96	2833.88	1019.42	496.28	114.88	168.60	75.21
Salivary glands	4089.67	7355.99	6930.99	4544.42	6233.26	363.64	494.42	3570.25
Skin	292.24	512.18	420.73	308.08	147.07	72.80	132.99	130.64
Remainder								
Lymphatic nodes	157.19	292.73	262.23	192.76	242.10	29.65	31.13	154.16
Muscle	157.19	292.73	262.23	192.76	242.10	29.65	31.13	154.16
Extrathoracic airway	2982.09	5530.58	4995.11	3707.09	4148.76	549.04	590.29	2586.57
Oral mucosa	3615.70	6721.28	6081.10	4476.34	5608.16	667.56	710.23	3694.11

Table 7. Equivalent dose (μSv) at various organ and tissues exposed on the low dose exposure setting according to the imaging modes

Organ/tissues	C mode	P mode		I mode		D mode		
		Maxilla	Mandible	Maxilla	Mandible	Maxillary incisor	Maxillary molar	Mandibular molar
Bone marrow	271.19	326.80	331.62	88.07	95.28	28.70	28.38	66.42
Oesophagus	25.21	27.69	19.26	10.25	20.41	4.05	4.13	8.76
Thyroid	452.07	501.65	442.15	189.26	405.79	63.64	68.60	198.35
Bone surface	1258.33	1516.34	1538.71	408.66	442.12	133.16	131.69	308.20
Brain	1044.63	1450.41	1884.30	516.53	257.02	428.51	474.38	122.31
Salivary glands	2611.16	3986.78	3618.60	2110.95	2886.36	277.27	314.88	2282.23
Skin	196.14	285.57	252.22	163.47	80.08	50.08	70.70	93.17
Remainder								
Lymphatic nodes	105.11	158.24	141.05	91.74	112.78	27.52	20.56	99.03
Muscle	105.11	158.24	141.05	91.74	112.78	27.52	20.56	99.03
Extrathoracic airway	1987.19	2982.58	2675.00	1762.26	1937.47	492.56	388.84	1664.53
Oral mucosa	2418.39	3660.12	3254.75	2130.89	2604.96	650.52	463.43	2371.80

serted into a linear regression model to calculate the conversion coefficients for each CBCT examination. The linear regression analysis was performed using the IBM SPSS software (version 19, IBM Corp., Somers, NY, USA).

Results

DAP

The DAP values for each mode and exposure setting of CBCT used in this study are shown in Table 5. At the adult exposure level, the DAP values were 3704 mGycm^2, 4499 mGycm^2, 1910 mGycm^2, and 644 mGycm^2 in the C, P, I, and D modes, respectively.

The patient effective dose

The equivalent and effective doses for each CBCT examination are shown in Tables 6-9. The effective doses in the adult exposure setting were 183.07 μSv in the C mode and 303.66 μSv and 288.48 μSv in the P mode for the maxilla and mandible, respectively. Additionally, the effective doses for the I mode in the maxilla and mandible were 145.85 μSv and 184.33 μSv, respectively. In the D mode, the effective doses were 22.34 μSv, 25.26 μSv, and 93.67 μSv for the maxillary incisors, maxillary molars, and mandibular molars, respectively.

The conversion coefficients

The conversion coefficients for each of the eight different CBCT examinations are shown in Table 10. For the C mode, the P mode at the maxilla, and the P mode at the mandible, the conversion coefficients were 0.049 μSv/mGycm^2, 0.067 μSv/mGycm^2, and 0.064 μSv/mGycm^2, respectively. For the I mode, the conversion coefficients

Table 8. Effective dose (μSv) on the adult standard exposure setting according to the imaging modes

Organ/tissues	C mode	P mode		I mode		D mode		
		Maxilla	Mandible	Maxilla	Mandible	Maxillary incisor	Maxillary molar	Mandibular molar
Bone marrow	51.26	75.31	73.11	23.46	26.10	5.15	4.95	11.44
Oesophagus	1.11	1.78	1.43	0.68	1.74	0.10	0.24	0.69
Thyroid	21.32	36.76	32.86	16.13	34.88	3.97	4.17	12.63
Bone surface	19.82	29.12	28.27	9.07	10.09	1.99	1.92	4.42
Brain	15.30	25.55	28.34	10.19	4.96	1.15	1.69	0.75
Salivary glands	40.90	73.56	69.31	45.44	62.33	3.64	4.94	35.70
Skin	2.92	5.12	4.21	3.08	1.47	0.73	1.33	1.31
Remainder								
Lymphatic nodes	1.45	2.70	2.42	1.78	2.23	0.27	0.29	1.42
Muscle	1.45	2.70	2.42	1.78	2.23	0.27	0.29	1.42
Extrathoracic airway	27.53	51.05	46.11	34.22	38.30	5.07	5.45	23.88
Oral mucosa	33.38	62.04	56.13	41.32	51.77	6.16	6.56	34.10
Effective dose (total)	183.07	303.66	288.48	145.85	184.33	22.34	25.26	93.67

Table 9. Effective dose (μSv) on the low dose exposure setting according to the imaging modes

Organ/tissues	C mode	P mode		I mode		D mode		
		Maxilla	Mandible	Maxilla	Mandible	Maxillary incisor	Maxillary molar	Mandibular molar
Bone marrow	32.54	39.22	39.79	10.57	11.43	3.44	3.41	7.97
Oesophagus	1.01	1.11	0.77	0.41	0.82	0.16	0.17	0.35
Thyroid	18.08	20.07	17.69	7.57	16.23	2.55	2.74	7.93
Bone surface	12.58	15.16	15.39	4.09	4.42	1.33	1.32	3.08
Brain	10.45	14.50	18.84	5.17	2.57	4.29	4.74	1.22
Salivary glands	26.11	39.87	36.19	21.11	28.86	2.77	3.15	22.82
Skin	1.96	2.86	2.52	1.63	0.80	0.50	0.71	0.93
Remainder								
Lymphatic nodes	0.97	1.46	1.30	0.85	1.04	0.25	0.19	0.91
Muscle	0.97	1.46	1.30	0.85	1.04	0.25	0.19	0.91
Extrathoracic airway	18.34	27.53	24.69	16.27	17.88	4.55	3.59	15.36
Oral mucosa	22.32	33.79	30.04	19.67	24.05	6.00	4.28	21.89
Effective dose (total)	123.02	163.23	158.49	68.51	85.10	20.10	20.20	61.51

Table 10. Conversion coefficients (E/DAP) according to the CBCT imaging modes

Imaging modes	kV	mA	DAP (mGy cm^2)	E (μSv)	Conversion coefficient (E/DAP)
C mode standard	80	6	3704	183	0.049
	80	4	2485	123	
P mode for maxilla	80	9	4499	304	0.067
	80	5	2508	163	
P mode for mandible	80	9	4499	288	0.064
	80	5	2508	158	
I mode for maxilla	80	8	1910	146	0.076
	80	4	956	69	
I mode for mandible	80	8	1910	184	0.095
	80	4	956	85	
D mode for maxillary incisors	80	9	644	22	0.038
	80	6	429	20	
D mode for maxillary molars	80	9	644	25	0.041
	80	6	429	20	
D mode for mandibular molars	80	9	644	94	0.146
	80	6	429	62	

at the maxilla and mandible were 0.076 μSv/mGycm^2 and 0.095 μSv/mGycm^2, respectively. For the D mode at the maxillary incisors, molars, and mandibular molars, the conversion coefficients were 0.038 μSv/mGycm^2, 0.041 μSv/mGycm^2, and 0.146 μSv/mGycm^2, respectively.

Discussion

Recently, investigation into the patient dose exposed during CBCT examination has been of increasing interest due to the profound dissemination of CBCT equipment in dental practice. This study showed that the DAP values of the Alphard VEGA CBCT examinations ranged from 644 mGycm^2 to 4499 mGycm^2, the effective doses from 22 μSv to 304 μSv at the adult standard exposure. The voxel sizes in the CBCT scanner were 0.39 mm, 0.3 mm, 0.2 mm, and 0.1 mm in the C, P, I, and D modes, respectively. In practice, each mode serves a specific purpose. The C mode (200 mm × 179 mm) is primarily used for orthodontic analysis; the P mode (154 mm × 154 mm) for the evaluation of both impacted third molars or the diagnosis of lesions at the maxillofacial region; the I mode (102 mm × 102 mm) for implant treatment planning involving more than three teeth or for the diagnosis of a jaw cyst; and the D mode (51 mm × 51 mm) for implant treatment planning involving one or two teeth, one impacted tooth, the diagnosis of a small jaw cyst, or unilateral TMJ evaluation.

In descending order, the DAP values at the adult exposure setting were the highest in the P mode followed by the values in the C, I, and D mode. The differences among the DAP values tended to be proportional to the field size.[21] However, the DAP value in the C mode, the largest FOV, was lower than that in the P mode in this study. This may be because the tube current for the C mode was two-thirds of that in the P mode. This result is in agreement with a previous study that observed an increasing DAP value at each mode as the tube current value increased.[21]

The Health Protection Agency of the United Kingdom proposed the use of the DAP as the dose quantity for the regular assessment of patient dose for dental CBCT.[20,29] The Health Protection Agency Working Party on dental CBCT suggested that DRLs should be set for both adult and child radiography and the adult protocol should be that used for the placement of the upper first molar implant in a standard adult patient and the child measurement should be made using the clinical protocol used to image a single impacted maxillary canine in a 12 year old male.[20] Given the wide range of DAP measurements recorded for different CBCT models, it was not considered appropriate to derive a National Reference Doses based on the third quartile DAP measurement of a dose survey as this would be little benefit for dose optimization.[20] Instead they presented the achievable dose, which was based on the third quartile DAP value of a dose survey, where the X-ray field size had been normalized to an appropriate size to adequately image the two views proposed above, 4 cm diameter × 4 cm height cylindrical volume.[20] And an achievable dose of 250 mGycm^2 was proposed for the adult procedure based on data by 41 CBCT units.[20] The adjusted DAP value at D mode normalized to an area of 16 cm^2 was 396 mGycm^2. Since this value was higher than the achievable dose suggested by the Health Protection Agency, it was required to investigate methods to reduce patient dose in the CBCT device used in this study.

The effective doses are different according to the irradiated organs and areas of the body, despite being exposed by radiation with the same DAP value. The effective doses were calculated to determine the conversion coefficients at each mode of different sites. The effective doses at the adult exposure setting ranged from 22 μSv to 304 μSv across all CBCT examinations. These values were similar to those of Pauwels et al[9] who reported that the effective doses from 14 CBCT devices ranged from 19 μSv to 368 μSv. In this study, the effective dose for the P mode at the maxilla was the highest. This might be due to the high tube current and large FOV in the P mode as well as the involvement of the radiosensitive salivary glands at the maxilla. In the D mode, a high variation from 22 μSv to 94 μSv was found according to the irradiated regions, and the effective dose at the maxillary incisors was lowest, but that of the mandibular molars was the highest. The high irradiation among these radiosensitive salivary glands may have influenced these results.

Previous studies about the conversion coefficients for other imaging modalities in dental radiology reported 0.009-0.108 μSv/mGycm^2 for intraoral periapical radiography,[25] 0.087-0.131 μSv/mGycm^2 for panoramic radiography,[25] and 0.056-0.077 μSv/mGycm^2 for lateral cephalometric radiography (ICRP 2006, draft).[26] In this study, ICRP 103 tissue weighting factors were used to calculate the effective doses. In the D mode, the conversion coefficient for the maxillary incisors was the lowest and that for the mandibular molars was the highest. These results were similar to those from the intraoral periapical radiographic

study,[25] which showed the lowest conversion factors for maxillary incisor and highest for mandibular molar.[25] In addition, the conversion coefficients tended to be dependent on tube voltage.[25,26] However, we did not investigate the effect of tube voltage on the conversion coefficient because the CBCT scanner used in this study had a fixed tube voltage. Further research using a CBCT scanner with an adjustable tube voltage is needed.

In summary, the present study demonstrates the conversion coefficients in one CBCT device with fixed 80kV ranged from 0.038 μSv/mGycm^2 to 0.146 μSv/mGycm^2 according to the imaging modes and irradiated region and were highest for the D mode at the mandibular molar.

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