Effective dose assessment with optically stimulated luminescence dosimetry and Monte Carlo calculation in CBCT

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The Doctoral Dissertation submitted to the Department of Dentistry, and the Graduate School of Yonsei University in partial fulfillment of the requirements for the degree of Doctor of Philosophy

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감사의 글

긴 고민과 수고 끝에 의미 있는 인생 과제 하나를 마무리하게 되어 감회가 남다릅니다. 공부가 결코 쉬운 일이 아님을 느끼며 버거울 때도 있었지만 매일 똑같은 일상에서 벗어나 논문 준비로 느꼈던 긴장감은 기분 좋은 경험이기도 했습니다. 그동안 어려운 일도 많았지만 여러 선생님들의 도움으로 무사히 학위 공부를 마칠 수 있었고, 일일이 찾아 뵙고 인사를 드려야 하나 이런 인사말로 대신함을 송구하게 생각합니다.

논문 전 과정을 세심하게 지도해주신 한상선 과장님, 본인의 업무로 바쁜 와중에도 항상 밝은 얼굴로 큰 힘이 되어준 이채나 선생님, 늘 살뜰하게 챙겨주시는 전국진 교수님 진심으로 감사드립니다. 또한 바쁜 업무 중에도 도움을 아끼지 않았던 병원 식구들에게도 더불어 감사의 인사를 전합니다.

성실이란 큰 유산을 물려주신 사랑하는 부모님, 아직도 자식 뒷바라지로 당신들 고단한 노년의 무게도 잊으시고 늘 애쓰시는 모습 정말 감사드리고 결코 잊지 않겠습니다. 갑작스런 병환으로 많이 힘드실 시아버님과 병간호로 힘드신 시어머님께도 제 논문이 작으나마 위로가 될 수 있길 바라며 두 분의 변함없는 큰 사랑을 기억하겠습니다. 부족함 많은 아내를 20여년간 아낌없는 사랑으로 격려하고 지지해주는 남편 김태민씨, 이 논문 역시 당신의 응원이 없었다면 결코 엄두도 못 냈을 겁니다. 이 자리를 빌어 깊은 감사와 사랑을 전합

니다. 늘 바쁜 엄마 밑에서 반듯하게 잘 자라준 사랑하는 혜리와 준영! 세상 무엇과도 바꿀 수 없는 소중한 두 아이들로 인해 끝까지 포기하지 않고 이 자리까지 올 수 있었고 진심으로 고마움을 전합니다.

아내와 엄마의 소홀함을 늘 묵묵히 이해하고 견뎌주는 사랑하는 나의 가족에게 이 논문을 바칩니다.

2018년 6월 박창희

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Abstract

Effective dose assessment with optically stimulated luminescence dosimetry and Monte Carlo simulation in CBCT

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Objective: The aim of this study was to evaluate the effective dose of three different cone beam computed tomography (CBCT) units with optically stimulated luminescence dosimeters (OSLD). Also, this dosimetric measurement method was compared with Monte Carlo (MC) simulation in Alphard 3030 CBCT unit. Through the measurement process and obtained value, more practical and efficient method in acquiring the effective dose of a CBCT would be suggested.

Materials and Methods: Twenty-two optically stimulated luminescence dosimeters (OSLD) were calibrated and equipped in human anthropomorphic phantom of head and neck. The phantom with dosimetry was exposed respectively with C, P and I modes of Alphard 3030 (Asahi Roentgen Ind., Co. Ltd, Kyoto, Japan); Large Jaw and Jaw modes of RAYSCAN α+ (Ray Co. Ltd, Hwaseong-si, Korea); Facial and Dual Jaw modes of CS9300 (Carestream Dental LLC, Atlanta, Georgia). Dose recorded in dosimetry was obtained and

organ dose as well as effective dose were obtained in each examination mode of 3 CBCT units. The organ and effective dose were also obtained with MC simulation on three examination modes of Alphard 3030 CBCT unit. For MC simulation, PCXMC software (STUK, Helsinki, Finland) was used and dose-area-product (DAP) value was measured with DAP meter.

Results: The effective dose was the highest in C mode, Alphard 3030 and the lowest in Dual jaw mode, CS9300. When comparing the 10 x10 cm FOV mode of all 3 CBCT units, the effective dose was higher in order of Alphard 3030 (258.8 μSv), RAYSCAN α+ (213.8 μSv), and CS9300 (90.7 μSv). The organ dose was the highest in salivary gland and the lowest in bone marrow in the same FOV mode of 3 CBCT units. When compared the result of OSLD in Alphard 3030 with MC simulation, percent difference of the effective dose was 9.8~23.4%. Overall organ dose distribution was consistent in all different examination modes of Alphard 3030 CBCT unit.

Conclusion: The effective dose showed tendency of increasing as FOV increased regardless of the CBCT model. In addition, the effective dose varies depending on several other factors such as exposure conditions and geometry of the CBCT, thus the effective dose of various equipment should be examined in the future. Also, MC simulation is expected to be convenient assessment method because it was similar to the OSLD measured value according to the examination modes.

Keywords: Monte Carlo calculation, Dosimetry, Cone beam computed tomography, Optically stimulated luminescence dosimeters

I. INTRODUCTION

Radiation in dental diagnostic examination is relatively low compared to that of medical.[1,2] However, as cone beam computed tomography (CBCT) became largely performed for various purposes in dental clinics, we cannot say radiation dose in dentistry is very low any more.

CBCT scanners are used in many dental specialties, such as orthodontics, implantology, trauma and dental surgery and so on. Compared with conventional CT, they offer several advantages, a lower cost and a significant reduction in the imparted patient doses.[2,3] These devices offer both two-dimensional and three-dimensional images that are adapted to the clinical requirements for a correct diagnosis and treatment planning. These facts have fostered the recent growth in the number of manufacturers and models of CBCT.[4,5]

According to the 2016 statistics published by the National Health Insurance Service, 48% of all dental clinics in South Korea have CBCT scanners,[6] which is a higher rate than in many nations with advanced medical systems. Most of CBCT devices have a standard protocol available with acquisition parameters and voxel sizes that are appropriate for the average patient. Additionally, the user can select from a range of protocols the most suitable to the clinical requirements and anatomical characteristics of the patient. Because the radiation dose received by the patient depends primarily on the field of view (FOV) and the selected exposure parameters, it is important to choose the protocol that imparts the lowest patient dose while providing the required. To date, published dosimetric studies reflect a wide patient dose range to reach similar diagnostic task; however, the effective

dose from CBCT examinations is several to many times greater than conventional panoramic imaging and lower by more than an order of magnitude than reported doses for conventional CT.[7–9] In addition, CBCT units from different manufacturers vary in their doses by as much as 10-fold for a same field of view (FOV).[3]

Although the risk to a patient from 1 computed tomography or CBCT examination might not by itself be large, millions of examinations are performed each year, making radiation exposure from dental and medical imaging an important public health issue. It has been estimated that 1.5% to 2% of all cancers in the United States can be attributed to computed tomography studies alone.[10]

These facts, along with the appearance of new International Commission on Radiological Protection (ICRP) recommendations providing a revised and extended set of tissue weighting factors for the computation of effective dose makes it necessary to initiate new dosimetric studies, to quantify risks and to support the dose optimization process.[11-13]

Although patient's overall radiation dose increased in dentistry, dose evaluation method has not be developed very much. Throughout the literatures, effective dose assessment has been studied in various ways; TLD (thermoluminescence dosimeters), OSLD (optically stimulated luminescence dosimeter) or MOSFET (metal oxide semiconductor field effect transistor) with tissue equivalent phantoms, simple calculation using conversion coefficient from DAP value or MC simulation with virtual human phantoms.[14]

Among them, dose measurement with TLD in anthropomorphic phantoms has been traditional and most common method in dental radiation dose researches.[2,3,7,9,15,16] For the

physical phantoms used in these studies, the position and size of radiosensitive organs have been estimated. This method, although providing organ doses and effective dose values compatible with commonly accepted uncertainties in the assessment of these quantities, has a number of limitations. Several of these limitations are caused by the use of a limited number of TLDs for assessing doses in large organs or tissues, unless an adequate number of TLDs is used to minimize the variability of organ dose calculations.[9] Moreover, the TLD chip positioning can also be critical when a fraction of an organ is irradiated during the scan or for organs in the neighborhood of the scanned region.[17]

Recently there is a trend of displacing TLD with OSLD or MOSFET.[18,19] MOSFET provides fast reading of dosage as it connected to the electronic probe directly. In general, it has been widely acceptable for dosimetry in radiotherapy, due to its suitability for high range of dose.[20] But the recent study by Koivisto et al. reported that MOSFET is comparable to TLD in low-dose dental radiography.[21]

The basic phenomenological fundamentals of OSLD and TLD are the same while the TLD releases the energy, which was stored during irradiation, by heat and OSLD dose by light.[22] There are several advantages of OSLD over TLD such as, high sensitivity, preciseness and simple dosimeter preparation and readout. Based on these advantages, several literatures performed dose measurement with OSLD and they reported that it showed reliable result compared to the TLD method.[23] TLD has been a common dosimetry in dental field for a long time and there are not many studied based on OSLD measurement, yet.

Monte Carlo (MC) simulation is another dose assessment method which simulate x-ray photon interaction with body organs and calculate overall effective dose. This method simulates virtual photon interaction on human phantom and expect radiation dose. The personal computer-based Monte Carlo software program (PCXMC) is one of the frequently used programs for software calculation of patient doses in x-ray examinations and is commonly used for chest radiography or computed tomography (CT).[24] Compared to TLD measurement, the PCXMC software calculations are easier to perform with substantial accuracy.[24-26] The calculation simply requires inputting the exposure dose and the proper value for dose-determining factors. Exposure dose gives information about the amount of x-ray photon and dose-determining factors help to simulate behavior of each x-ray photon in the software.

Such method is advantageous in that it is simple to use since calibration and readout procedure are not required and the result is not dependent on the dosimeter types or its location in phantom.[27] However, this simulation is accurate only when it is based on the correct machine and radiation beam geometry, such as distance between the x-ray source to patient, beam rotation angle or vertical angle of x-ray beam. According to the incorrect combination of those factors, effective dose might show up to 51.24 % difference compared to the TLD measured value.[28]

Both OSLD measurement and MC simulation method are the short of data reported in dental x-ray equipment at present. There are only few studies of MC method compared to traditional dosimetry method using TLD or OSLD in dentistry.[28,29] In fact, as far as the

authors know, there are no English reported study on dose assessment in comparison of MC method and OSLD method in the dental field. More research on the newly introduced method, OSLD or MC simulation, compared to the traditional dosimetry should be performed to prove efficiency of these methods.

The aim of this study was to evaluate the effective dose of three different cone beam computed tomography (CBCT) units with optically stimulated luminescent dosimeters (OSLD). Also this dosimetric measurement method was compared with Monte Carlo (MC) simulation in Alphard 3030 CBCT unit. Through the measurement process and obtained value, more practical and efficient method in acquiring CBCT effective dose would be suggested.

II. MATERIALS AND METHODS

1. Cone beam computed tomography units and examination protocols

The equipment used were Alphard 3030 CBCT unit (Asahi Roentgen Ind., Co. Ltd, Kyoto, Japan), RAYSCAN α+ CBCT (Ray Co. Ltd, Hwaseong-si, Korea) and CS9300 (Carestream Dental LLC, Atlanta, Georgia).

Exposure conditions used in this study were as followed; In Alphard 3030, cephalometric, C mode (FOV = 20×20 cm), panoramic, P mode (FOV = 15.4×15.4 cm) and implant, I mode (FOV = 10.2×10.2 cm); In RAYSCAN α+, Large jaw mode (FOV = 16×10 cm), Jaw mode (FOV = 10×10 cm); In CS9300, Facial mode (FOV = 17×13.5 cm), Dual jaw mode (FOV = 10×10 cm). Detailed exposure conditions for each mode of three CBCT units were described (Table 1).

Table 1. Exposure conditions of different modes in three CBCT units.

Unit name	*Manufacturer*	*FOV size* H×W *(cm)*	*Tube voltage* (kV_p)	*Tube current (mA)*	*Exposure time (sec.)*	*Rotation angle (°)*	*Filtration (mwAl)*	*X-ray source to patient distance (cm)*
Alphard 3030	Ashahi Roentgen (Kyoto, Japan)	20×20 (C mode)	80	10	17	360	2.8	65
		15.4×15.4 (P mode)	80	8	17	360	2.8	65
		10.2×10.2 (I mode)	80	8	17	360	2.8	65
RAYSCAN α+	Ray co. (Hwaseong-si, Korea)	16×10 (Large Jaw mode)	90	12	14			
		10×10 (Jaw mode)	90	12	14			
CS9300	Carestream (Dental LLC, Atlanta, Georgia)	17×13.5 (Facial mode)	80	8	20			
		10×10 (Dual jaw mode)	80	8	12			

2. OSLD measurement

OSLD is a plastic disks infused with aluminum oxide doped with carbon (Al_2O_3:C). This dosimetry absorbs radiation and this stores energy that can be read out with light stimulation.[30] The dosimetry efficiently releases stored energy when stimulate with light of 540nm, still wide range of light can stimulate energy release thus the disk is encased in plastic holder. Each holder case is tagged with quick response (QR) code for identification of respective OSLD (Figure 1).

Total 22 OSLDs (Nano-Dot, Landauer, Inc., Glenwood, IL) were placed in and on head and neck organs of an average adult male head phantom (ATOM, CIRS, Norfolk, VA). This phantom was composed of tissue equivalent material and for each anatomy, there was slot for dosimetry placement (Figure 2). The phantom includes detailed 3-dimensional anthropomorphic anatomy including brain, bone, larynx, trachea, sinus, nasal cavities, and teeth. The bones contain both cortical and trabecular separations.

The phantom was modified by machining slots to accept OSL nanodot dosimeters at sites corresponding to the internal tissues of interest. A skin surface dosimeter in the back of the neck was positioned at the vertical center of the designated slice level and taped in position. Lens of eye dosimeters were centered over and inset in the anatomic location for the lens and taped in position. Internal dosimeters were positioned vertically with the upper edge of the dosimeter slot, flush with the surface of the selected slice level, and held in position by friction of the dosimeter case and the phantom material at the sampled anatomic location. Details of the OSLD locations and corresponding tissues were described (Figure 3).[23]

Figure 1. OSLD (Nanodot; Landauer Inc, Glenwood, USA).

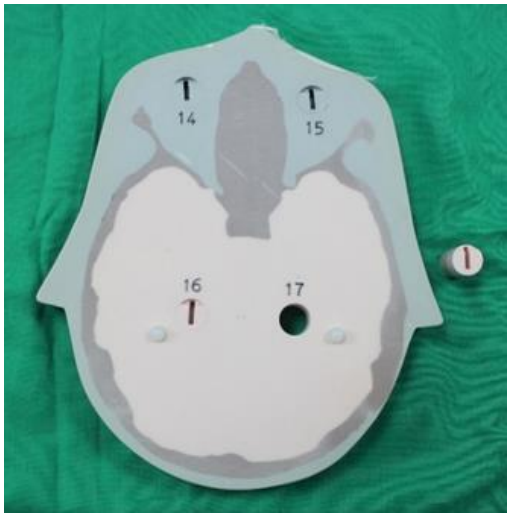
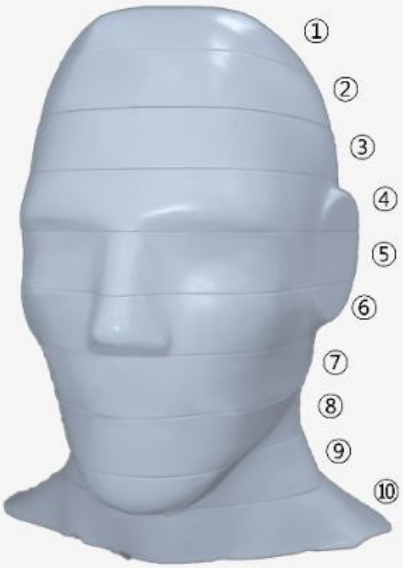


Figure 2. Dosimetry slots in ATOM phantom.



Slice number	Dosimetry number	Tissue
3	1	Calvarium Anterior
	2	Calvarium posterior
	3	Fronto-parietal lobe (Right)
4	4	Parieto-occipital lobe (Left)
	5	Fronto-parietal lobe (Left)
	6	Fornix (Right)
	7	Lens of eye (right)*
5	8	Lens of eye (Left)*
	9	Pituitary (Right)
	10	Pituitary (Left)
6	11	Maxillary sinus (right)
	12	Maxillary sinus (Left)
	13	Buccal cheek (right)*
7	14	Parotid gland (right)
	15	Parotid gland (left)
8	14	Ramus (right)
	15	Ramus (Left)
	16	Oropharyngeal airway
	17	Submandibular gland (right)
	18	Submandibular gland (left)
	19	Esophagus
9	19	Cervical spine
	20	Lateral and back of neck (left)*
10	21	Thyroid (left)
	22	Thyroid (right)

* Dosimeters directly attached on the skin

Figure 3. OSLD locations and corresponding tissues.

All exposures were performed for twice and read dose values were averaged for the further calculation. During scanning the phantom was oriented with its section planes approximately parallel to the scan rotation plane (horizon). A phantom position simulating the positioning of a patient on the chin rest was used (Figure 4).

The reader (MicroStar; Landauer) was prepared to be optimized for 80 kilovoltage and low dose type (<30 mGy) and each dosimetry was identified with QR code and read out. The values were acquired as a photon counts with an accuracy of approximate ± 2 % and this was converted to the dose in milligrays (mGy) unit using an energy-specific conversion factor (Figure 5). Those were converted into organ dose, mostly following the method done by Ludlow et al.[23]

The products of these values and the percentage of a tissue or an organ irradiated in a radiographic examination were used to calculate the equivalent dose in microsieverts (μSv) unit (Table 2).

Figure 4. ATOM phantom positioned in CBCT unit.

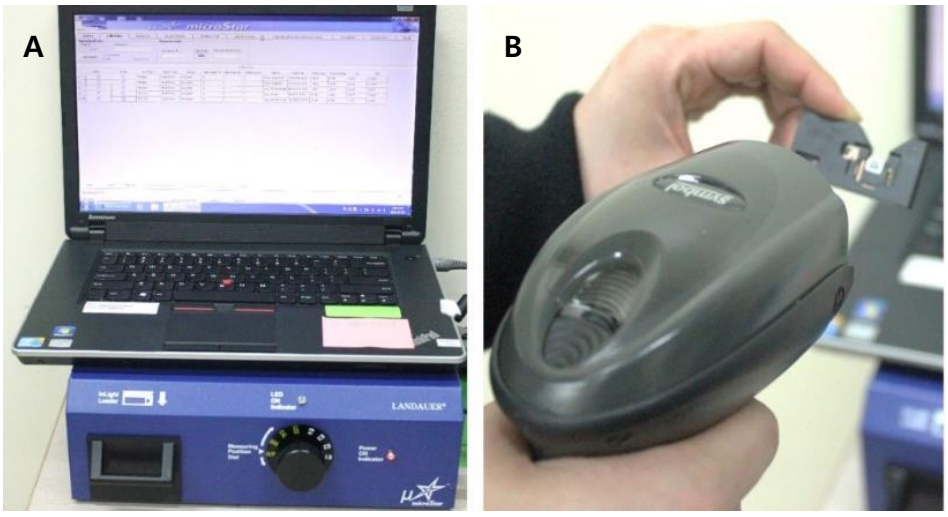


Figure 5. OSLD reading process. A, OSLD reader (MicroStar; Landauer); B, OSLD reading.

Table 2. Estimated fraction irradiated on tissues, tissue weighting factors recommended by the International Commission on Radiological Protection(ICRP), and OSLD used.

	Fraction irradiated (%)	Tissue weighted factor	OSLD ID
Bone marrow	12.2	0.12	
Mandible	0.8		14, 15
Calvaria	7.7		1, 2
Cervical spine	3.8		19
Thyroid	100	0.04	21, 22
Esophagus	10	0.04	16
Skin	5	0.01	13, 20
Bone surface*	16.5	0.01	
Mandible	1.3		14, 15
Calvaria	11.8		1, 2
Cervical spine	3.4		21
Salivary glands	100	0.01	
Parotid	100		14, 15
Submandibular	100		17, 18
Brain	100	0.01	3, 4, 5, 6, 9, 10
Remainder tissue		0.12	
Lymphatic nodes	5		14, 15, 17, 18, 19
Muscle	5		14, 15, 17, 18, 19
Extrathoracic airways	100		14, 15, 16, 17, 18
Oral mucosa	100		14, 15, 16, 17, 18, 19
Eyes	100		7, 8

*Bone surface = bone marrow dose x bone/muscle mass energy absorption coefficient ratio (MEACR), MEACR = -0.0618 x 2/3 kVp + 6.9406 [31]

When multiple OSLDs were used for one organ, the average value was used. For example, the mean value of fronto-parietal lobe, parieto-occipital lobe, fornix and pituitary were used for brain dose. The bone marrow equivalent dose was calculated for the calvaria, mandible, and cervical spine. The distribution of active bone marrow for an adult body is known to be 7.7 % for the calvaria, 0.8 % for the mandible, and 3.8 % for the cervical spine.[32] For the bone surface dose, bone marrow dose was multiplied by bone/muscle mass energy absorption coefficient ratio (MEACR) according to the data from the National Bureau of Standards handbook No. 85.[31] The equation for the coefficient was as followed: -0.0618 x kV(p) x 2/3 + 6.9406.[31] The irradiated proportion of skin, lymphatic nodes and muscles on head and neck region were estimated as 5 % and esophagus as 10 % of the whole body and these were took consideration in organ dose calculation (Table 2).[33]

The organ doses were further integrated into the effective dose considering tissue weighted factor provided by International Commission on Radiological Protection (ICRP) 2007 (Table 2).[23,34]

The effective dose (E) is a calculation that permits comparison of the detriment of different exposures to ionizing radiation to an equivalent detriment produced by a full-body dose of radiation. Effective dose, expressed in microsieverts (μSv) unit, was calculated with the equation: $E = \sum W_T \times H_T$, where E is the summation of the products of the tissue weighting factor (W_T), which represents the relative contribution of that organ or tissue to the overall risk, and the radiation weighed dose (H_T). The whole-body risk is determined by the summation of the radiation-weighted doses to all tissues or organs exposed.

3. Monte Carlo simulation

Monte Carlo (MC) simulation is a widely used technique in the probabilistic analysis where random numbers are used for simulating the transport of radiation in complex medium such as human body.[35] When the physical information about x-ray examination technique is given, computer calculates organ absorbed dose with a MC simulation.

In this study, commercial software commonly used in medical radiation dose calculation, PCXMC20Rotation, a supplemental program of PCXMC 2.0 (STUK, Helsinki, Finland), was used for dose calculation of Alphard 3030 CBCT unit.

According to the PCXMC20Rotation software manual, following factors were set for the software running; input dose, reference point, x-ray tube voltage, filtration, source-to-reference distance, x-ray beam width and height at reference point.

As an input dose, the exposure dose from the unit, dose-area-product (DAP, mGy·cm^2) was selected and measured with DAP meter (VacuDAP^{TM}; VacuTec Meßtechnik GmbH, Dresden, Germany). For respective examination mode of Alphard 3030 CBCT unit, measurement was performed twice and average value was used to minimize the measurement error. And the measured values were corrected with the coefficient for the temperature and atmospheric conditions (Figure 6).

The reference point, the center of the x-ray unit during rotating through which all x-ray beams pass, was referenced to the previous literatures and marked as 3 dimensional coordination on X, Y, Z-axis. The software roughly depicted this point as 0, -5, 82 cm on the X, Y, and Z-axis, respectively (Figure 7).[36] In the C, P and I modes of Alphard 3030

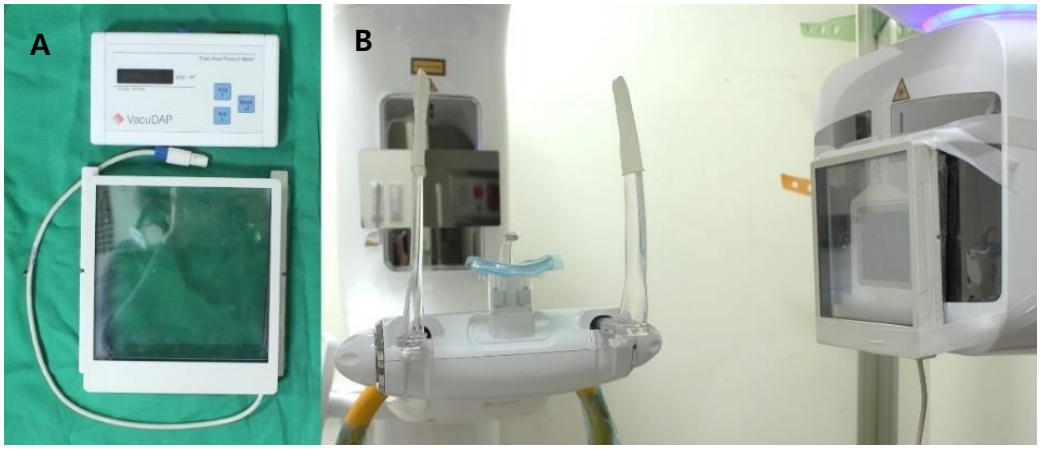


Figure 6. A, DAP meter (VacuDAP™; VacuTec Meßtechnik GmbH, Dresden, Germany); B, DAP measurement in CBCT unit.

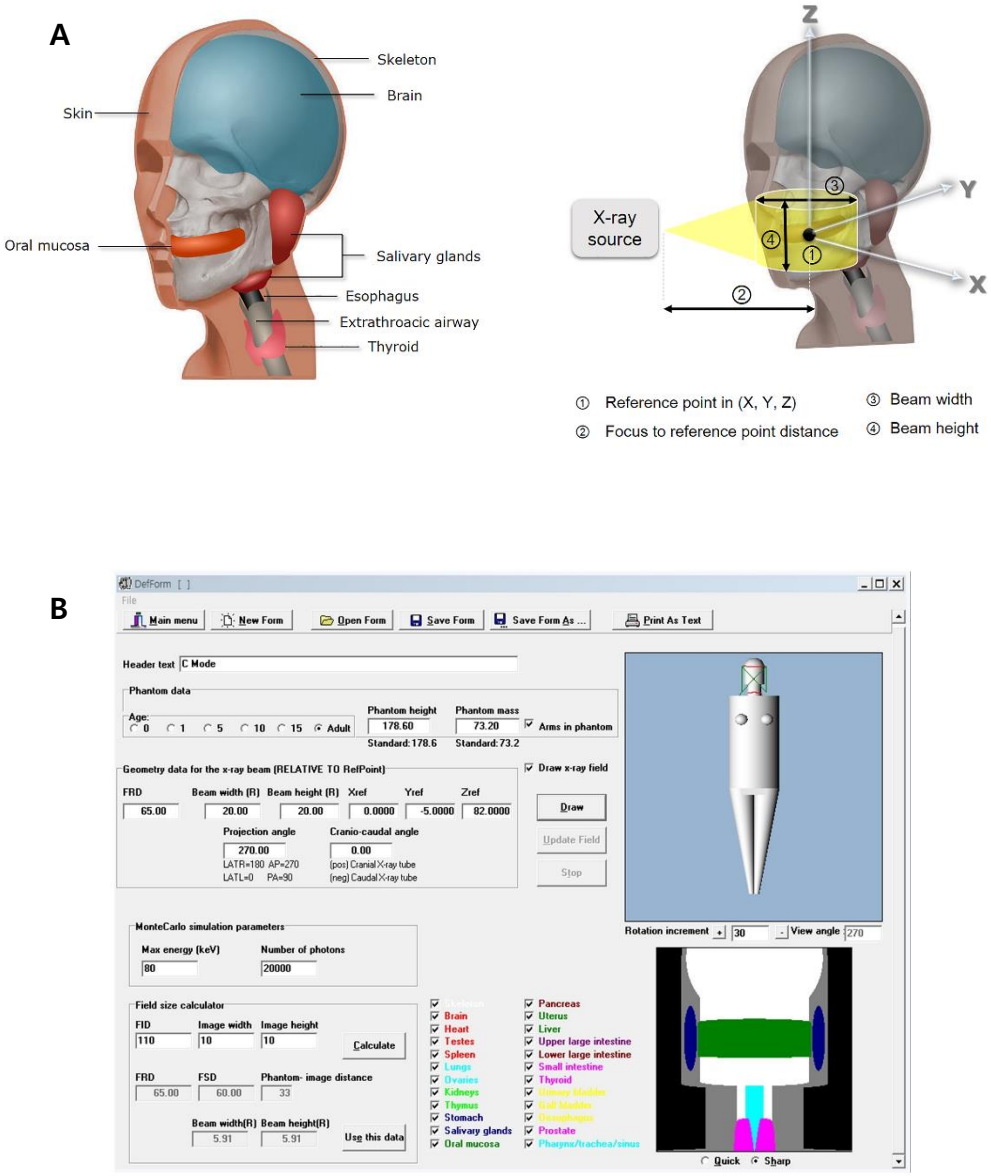


Figure 7. A, Schematic view of reference point, focus-to-reference point distance, beam width and height; B, PCXMC software (STUK, Helsinki, Finland).

CBCT unit, the reference point was at the center of the dental arch.

In addition, x-ray tube voltage, filtration, source-to-reference distance, x-ray beam width and height at reference point, were according to each examination mode in the specifications of Alphard 3030 CBCT unit, provided by each manufacturer (Table 1).

4. Data analysis

The effective doses of three different CBCT units were evaluated and the effective doses of the same FOV (10×10cm) were comparatively analyzed with OSLD measurement.

The differences of the effective dose from MC simulation were obtained in percent difference (%) compared to that of OSLD method, according to each different examination mode of Alphard 3030 CBCT unit. The difference between the two values was divided by the average of the two values and multiplied by 100 to obtain percent difference. Organ absorbed doses obtained with both methods were also compared respectively according to each examination mode of the Alphard 3030 CBCT unit.

III. RESULTS

Effective doses were increased with increasing FOV size in all 3 CBCT units. The effective dose was the highest in C mode, Alphard 3030 (599.0 μSv) and the lowest in Dual jaw mode, CS9300 (90.7 μSv) (Table 3).

When comparing the 10×10 FOV mode of all 3 CBCT units, the effective dose was higher in order of Alphard 3030 (258.8 μSv), RAYSCAN α+ (213.8 μSv), and CS9300 (90.7 μSv), and organ absorbed doses were the highest in salivary gland and the lowest in bone marrow. Overall organ absorbed doses distribution was consistent in the same FOV mode of all 3 CBCTs (Figure 8).

The mean DAP value measured with DAP meter was 5621.5, 5047.0 and 2351.0 $mGy \cdot cm^2$ respectively for C, P and I mode of Alphard 3030 (Table 4).

The effective dose differences between OSLD and MC method in the Alphard 3030 CBCT unit were obtained by percentage difference (%) and presented in Table 5. When compared the result of OSLD in Alphard 3030 with MC simulation, OSLD measured effective dose showed the tendency of higher value than that obtained with MC simulation. The percent difference between the two methods was in the range of 9.8 to 23.4 %. It was decreased as the examination FOV decreased (Table 5).

Organ absorbed doses were varied according to the method, while overall trend was similar in both methods (Figure 9). In other words, the organs irradiated relatively low dose in OSLD method mostly showed low dose in MC simulation. Organs with high dose in

Table 3. OSLD measured absorbed (*mGy*) and effective doses (*μSv*) of three CBCT units.

											Remainder group components			
Unit name	*Manufacturer*	*Mode (FOV, cm)*	*Effective doses (μSv)*	*Bone marrow*	*Bone surface*	*Skin*	*Esophagus*	*Brain*	*Thyroid*	*Salivary glands*	*Lymph nodes*	*Muscle*	*Extrathoracic airway*	*Oral mucosa*
Alphard 3030	Ashahi Roentgen (Kyoto, Japan)	C mode (20×20)	599.0	0.18	1.29	0.45	3.27	4.45	6.40	4.74	0.22	0.22	4.59	4.37
		P mode (15.4×15.4)	448.3	0.07	0.50	0.34	2.22	2.66	4.96	4.43	0.20	0.20	4.25	3.91
		I mode (10.2×10.2)	258.8	0.01	0.09	0.28	1.11	0.39	2.57	4.04	0.17	0.17	3.67	3.25
RAYSCAN α+	Ray co. (Hwaseong-si, Korea)	Large Jaw mode (16×10)	228.5	0.01	0.09	0.15	0.93	0.38	1.68	4.54	0.19	0.19	4.21	3.66
		Jaw mode (10×10)	213.8	0.01	0.09	0.13	1.03	0.57	1.50	3.93	0.17	0.17	3.76	3.31
CS9300	Carestream (Dental LLC, Atlanta, Georgia)	Facial mode (17×13.5)	181.4	0.02	0.10	0.20	0.86	1.01	1.21	3.16	0.13	0.13	3.08	2.71
		Dual jaw mode (10×10)	90.7	0.01	0.04	0.11	0.34	0.23	0.58	1.95	0.08	0.08	1.80	1.56

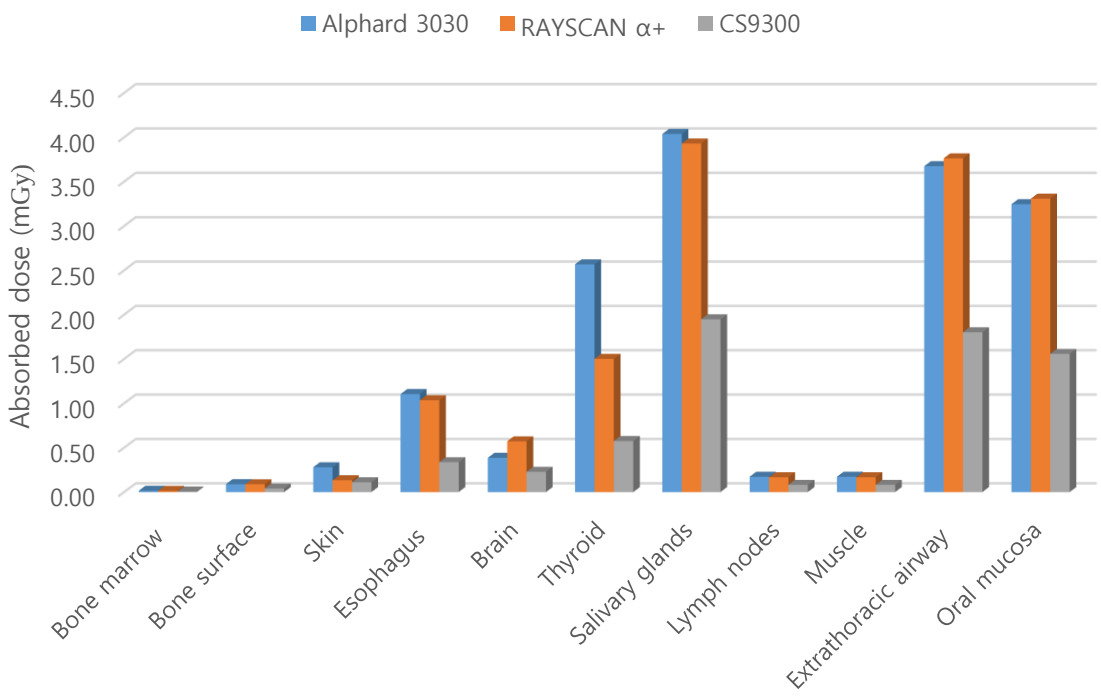


Figure 8. Organ absorbed doses distribution of 3 CBCT units with same FOV size (10×10 cm).

Table 4. Mean and standard deviation of Dose-Area-Product (DAP) value measured with DAP meter (mGy·cm^2) in different modes of Alphard 3030 CBCT unit.

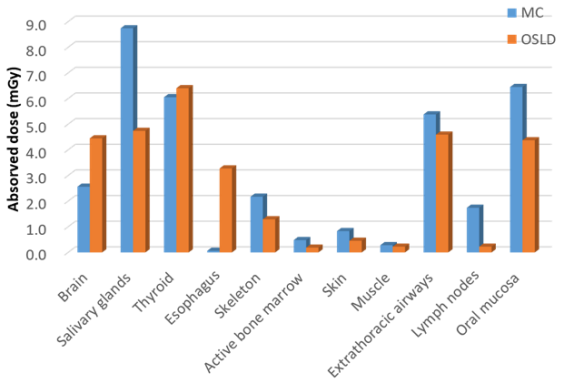
C mode	P mode	I mode
5621.5 ± 3.5	5047.0 ± 2.8	2315.0 ± 2.8

Table 5. The effective dose obtained with OSLD method and MC calculation, and the percent difference in Alphard 3030 CBCT unit.

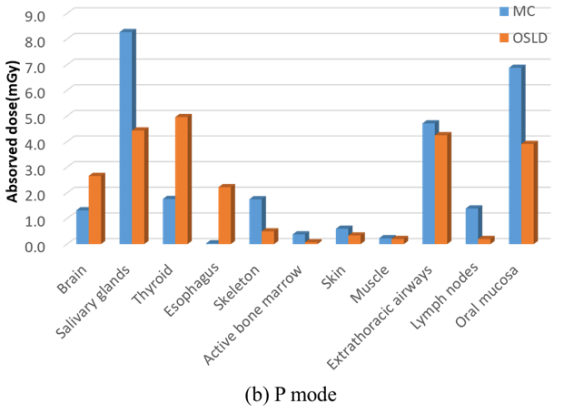
	Effective dose (μSv)		
	C mode	P mode	I mode
OSLD method	599.0	448.3	258.8
MC simulation	473.5	404.8	234.4

	Percent difference (%)*		
	C mode	P mode	I mode
	23.4	10.2	9.8

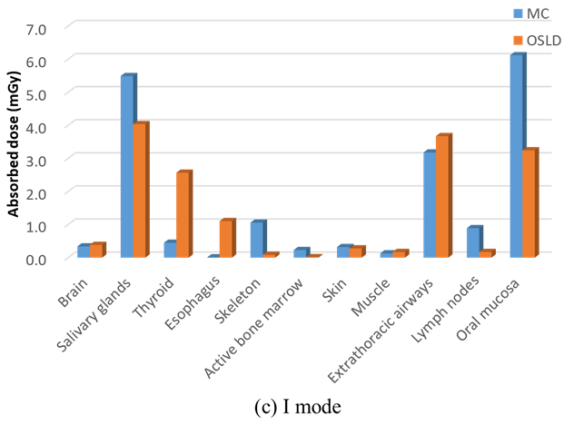
* Percent difference = $\left| \frac{effective\ dose\ (\text{OSLD method}) - effective\ dose\ (MC\ method)}{\frac{effective\ dose\ (OSLD) + effecitve\ dose\ (MC)}{2}} \right| \times 100$



(a) C mode



(b) P mode



(c) I mode

Figure 9. Organ absorbed doses distribution of both methods according to each examination mode of Alphard 3030 CBCT unit.

OSLD method also showed high dose in MC simulation. In OSLD method, thyroid in C and P mode, salivary gland in I mode were the most irradiated organ. In MC method, salivary gland in C and P mode, oral mucosa in I mode showed highest dose value.

The absorbed dose for bone marrow showed the lowest value in the OSLD method, while the esophagus showed the lowest value in the MC simulation. The absorbed doses varied by organ more severely in the MC simulation than in the OSLD method.

IV. DISCUSSION

Since the development of CBCT in the dental field, it's use has been growing rapidly, and research on its radiation dose has always been of interest. For now, various CBCT models from numerous manufacturer equipped with different exposure mode. In other words, exposure dose as well as patient absorbed or effective dose are varied on each CBCT machines of different examination modes.

In 2015, Ludlow et al. meta-analyzed the effective dose of various CBCT units conducted with traditional dosimetric methods, based on the tissue weighted factor of ICRP 2007 recommendation.[37] The value was widely varied from 46 to 1073 μSv for large field of view (FOV), 9-560 μSv for medium FOV and 5-652 μSv for the small FOV in each machines.[37] Assumed C and P mode (Alphard 3030) as large, I mode (Alphard 3030), Large jaw and Jaw mode (RAYSCAN α+), Facial and Dual jaw mode (CS9300) as medium, our study showed effective dose included in this range, regardless of the measured method. In case of CS9300 CBCT unit, effective dose was slight lower than our results, 76 μSv for Dual jaw mode.[37]

The major contribution to the wide range of effective dose would be probably different exposure conditions of each machines, however, different dose measurement method also influenced to raise deviations of overall effective dose assessment.[37] Kim et al. studied the effective dose with TLD and the CBCT unit of the same manufacturer but different model as in the present study, reported 288, 184 μSv respectively for P, I mode.[38] Although the

experiment was not conducted with the exact same exposure conditions, it was interesting that the MC method showed closer values than that of the OSLD measurement. Recent study, compared MC method with TLD measurement in CBCT, reported both methods were in agreement of 10.1 %.[29] This might be due to the fact that the OSLD measurement is sensitively depend on the experiment setting. Unlike phantom used with TLD, number of dosimetry-holding slot is very limited in OSLD phantom. Also, the slot location in the phantom is customized when purchasing it, thus the location might be varied by individual phantom. This might be contributed to unexpected result showing large deviation between TLD and OSLD compared to that between TLD and MC method. Ludlow et al. stated that the dose measurement with dosimeters may show critically different result according to the sampling method.[37] This means that the location, distribution and the number of dosimeter used in each organ can influence greatly for the measure value. The dosimeter location within each organ could be standardized with the same dosimeter housing slots and slice number for human phantom, still it may be difficult to standardize dosimeter numbers, due to the practical reason such as cost of dosimetry. Previous literature reported that the organs prominently contributing to effective dose was remainder tissues.[9] Due to the sampling error of dosimetry, remainder tissues which distributed on overall body (muscle or lymph nodes) or covering large area (pharyngeal and oral mucosa), may resulted large errors in measured dose. In fact, skin and skeleton were the tissues showing highest difference over 160 % in dose, when our result was compared to the previous study performed in the same exposure condition.[38] Also the results of the present study showed that effective dose

differences between the two methods were greater in the examination mode with larger FOV. It can be suspected that x-ray irradiated to large area more tissues affected and sampling error inevitably increases. In addition, phantom positioning within the CBCT unit during the exposure is another challenging part to make accordance even though this may raise large deviation in resulting organ dose and the effective dose.

On such aspect, application of MC simulation might be more practical. During the whole measurement process, user dependent factors were limited in MC simulation. According to the previous studies adopted MC simulation for dose evaluation, machine geometry, such as filtration, tube voltage, x-ray beam width or height and source-to-subject distance, are the information required for the simulation.[28,39,40] For the current study, manufacturer of the machine provided required information in the specification. This simulation is also efficient in that it cost less than preparing human tissue-equivalent phantom, dosimetry, and dosimetry reading device.

But there is important consideration for adopting MC simulation currently. The virtual phantom used for the simulation should be standardized.[41]

In 2009, ICRP introduced reference phantom of female and male adult which is based on the actual computed tomographic data of adult human.[42] Among previous studies, only one adopted ICRP reference phantom and others used computed tomographic scan data of Rando-Alderson phantom.[17,29] In present study, the Cristy and Eckerman phantom facilitated in software was used without any modification. The human body and organs were mapped in this phantom in rough and rudimentary ways, such as using simplified

geometrical approximations like flat surfaces, cones, circles or ovals. And these calculations were conducted on a very simplified position of the organs in the phantom. Compared to the ICRP reference phantom, it is not sophisticated enough to simulate precise organ absorbed and effective dose in dental CBCT, exposing relatively low dose compared to medical CT. This could raise the distortion in the organ doses. And this probably contributed to the difference between the dose from OSLD method and MC simulation, as well, in this study. In addition, thyroid absorbed dose was higher in OSLD method compared to MC calculation in P and I modes. This was thought to be due to different thyroid location in phantom of two methods.

Likewise, Koivistro et al. reported that the effective dose value differs by 52 % due to the differences in the shape, volume, and positioning of the thyroid gland in the measurement phantom and the PCXMC model phantom.[36]

Zhang et al. implicated that the phantom plays an important role in calculating dose of head and neck region. They conducted Monte Carlo simulated dose calculation on different four phantoms with the same cone beam CT system. The resultant organ dose showed differences more than 100 %, even though the effective dose under 30 %.[41] There are current efforts to develop more complicated and sophisticated phantoms such as voxel phantoms or hybrid phantoms.[43,44] For future studies with more reliable organ dose calculations, software with a more developed phantom will be required.

Another new point of our study was the type of dosimeters that were used. OSLD has several advantages over TLD such as, high sensitivity, preciseness and simple dosimeter

preparation and readout. Each dosimeter has a QR code, enabling easy identification and tracking throughout the study. Also OSLDs can be read within minutes of exposure, allow for multiple nondestructive reads, and can be erased and reused. This is meaningful because this study would have required more separate dosimeters if TLDs had been used, some of which would most likely have failed during the destructive read process. Therefore, testing the many examination modes in multiple CBCT units would have been less practicable without the OSL dosimeters.[23]

Effective dose values between MC simulation and OSLD method showed the largest difference of 23.4 % in the C mode with large FOV size and the smallest 9.8 % in the I mode with small FOV size in our study. According to Toivonen et al,[45] the difference between both methods was indicated below 25 % as good agreement. Because the difference between MC simulation and OSLD method was less than 25 % in all FOVs in the present study, the both methods might be good agreement in all examination modes of Alphard 3030. In dental CBCT exposing relatively low dose compared to multidetector CT, still the dosimetric method seems more accurate.

In 2015, Ludlow et al. mentioned that DAP is not appropriate to be used for obtaining effective dose.[37] This statement is true, if we simply convert DAP value into effective dose using converting coefficient. Several studies attempted to find converting coefficient to obtain effective dose of CBCT, while coefficients are different by individual CBCT model with unique geometry.[38,46] On the contrary, MC simulation calculates the effective dose taking individual machine geometry into the consideration. Thus, it may produce more

precise results based on the DAP value, compared to the simple conversion method of DAP value into effective dose. In the present study, DAP measurement was performed using DAP meter. DAP measurement procedure is not experimenter specific, still, it requires equipment composed of ion chamber, DAP meter and cables. Also, the procedure takes time and experimenter's labor. DAP values may be displayed in the console of several current CBCT devices, and this quantity has the potential to be used as a broad estimate of effective dose using suitable conversion factors.[47]

Though, this value is not real-time measured, and predetermined value by the manufacturer, MC simulation software with precise reference phantom, it may be possible to obtain an approximate effective dose which is not depended on the experimenter or the measurement method.

In the quest to lower the dose of ionizing radiation administered to patients, dramatic reductions are meaningless if image quality degrades to the point of being non-diagnostic. The ongoing challenge in the optimization of CBCT is to reduce the dose without drastically decreasing image quality and diagnostic information. One potential means of reducing patient risk from CBCT examinations is to limit the area of exposure using variable FOVs that are sized for the location of the anatomy of interest. However, voxel size is linked to FOV in many CBCT units, and smaller voxel sizes associated with smaller FOVs can actually increase the dose because of increases in exposure that are needed to maintain an adequate contrast-to-noise ratio. As optimization and dose reduction become more of a focus for CBCT manufacturers, the effects on image quality will need close

attention. Published evidence establishing the usability of low-dose and low-quality scans for diagnostic purposes in dentistry is limited. Therefore, further research in this field will be needed in the future. The effective dose by individual CBCT models and examination modes is continuously reported and large data has been accumulated up to now.[9,37] To contribute for this big data accumulation, the effective dose obtained by OSLD method in various CBCT units were reported in this study. The ultimate goal of the effective dose assessment and data accumulation is a dose reduction and regulation for patient's benefit.

To attain this, more importantly, consensus in dose evaluation method is essential. In addition, development of a relatively accurate and easy-handling method would contribute more dose data acquisition. Therefore, we carefully suggest MC simulation based on reference phantom for further dose evaluation.

V. CONCLUSION

1. The effective dose was the highest in C mode, Alphard 3030 and the lowest in Dual jaw mode, CS 9300. The effective dose in the 10×10 cm FOV mode was higher in order of Alphard 3030, RAYSCAN α+ and CS 9300.

2. OSLD method showed the highest organ dose in salivary gland and the lowest value in bone marrow in the same FOV mode of all 3 CBCT units.

3. The percent difference of the effective dose between OSLD method and MC simulation was ranged from 9.8~23.4 %, which is a clinically acceptable range.

4. The organ dose distribution showed relatively similar tendency in both OSLD method and MC simulation.

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Abstract (Korean)

광자극발광선량계(OSLD)측정법과 몬테카를로 산출법(MC)에 의한 콘빔시티의 유효선량 평가

목적: 광자극발광선량계(OSLD)를 이용하여 세 종류의 콘빔시티에서 유효선량을 측정하고, Alphard 3030 콘빔시티에서 OSLD 측정값과 몬테카를로(MC) 시뮬레이션 산출값을 비교하는 것이다. 이를 통해 콘빔시티 유효선량을 획득하기 위한 보다 실용적이고 효율적인 방법을 제안하고자 한다.

재료 및 방법: 초기 보정을 거친 22개의 OSLD를 성인 두경부를 재현한 ATOM (CIRS, Norfolk, VA) 팬텀의 정해진 위치에 각각 삽입하였다. 준비된 팬텀을 세 종류의 콘빔시티를 이용하여 제조사가 제시한 노출조건으로 촬영하였다. Alphard 3030 콘빔시티(Asahi Roentgen Ind., Co. Ltd, Kyoto, Japan)에서 C, P, I 3가지 모드, RAYSCAN α+ 콘빔시티(Ray Co. Ltd, Hwaseong-si, Korea)에서 Large jaw, jaw 2가지 모드, CS9300 콘빔시티(Carestream Dental LLC, Atlanta, Georgia)에서 Facial, Dual jaw 2가지 모드로 각각 촬영하였다. 모드 별로 OSLD 측정값을 얻고, 장기 흡수선량과 유효선량을 산출하였다. 또한 Alphard 3030의 3가지 모드에서는 선량면적곱측정계 DAP meter (VacuDAP^{TM}; VacuTec Meßtechnik GmbH, Dresden, Germany)로 노출선량을 측정하였다. 이 값을 통해 PCXMC 소프트웨어(STUK, Helsinki, Finland)를 사용하여 몬테카를로 산출법으로 장기 흡수선량과 유효선량을 획득하였다. OSLD와 MC 두 방법 간의 유효선량 차이를 % 오차로 비교하였다.

결과: OSLD로 측정한 유효선량은 Alphard 3030 C 모드에서 가장 높았고 (599.0 μSv), CS 9300 Dual jaw 모드에서 가장 낮았다 (90.7 μSv). 조사야 크

기가 10×10 cm으로 동일한 모드 간의 유효선량을 비교하면 Alphard 3030 (258.8 μSv), RAYSCAN α+ (213.8 μSv), CS9300 (90.7 μSv) 순서대로 높게 나타났다. 장기별 흡수선량은 콘빔시티의 종류와 상관없이 타액선에서 가장 높았고, 골수에서 가장 낮았다.

Alphard 3030 콘빔시티의 OSLD 측정값과 MC 산출값을 비교해보면, 유효선량의 두 방법 간 퍼센트 오차는 9.8~23.4 %를 보였다. 두 방법 간의 장기별 흡수선량의 전반적인 분포는 Alphard 3030 콘빔시티의 검사 모드와 상관없이 비슷한 양상을 보였다.

결론: MC 산출값은 검사 모드에 따른 OSLD 측정값과 유사한 수준의 결과를 보였다. 따라서 MC 산출법은 임상에서 사용할 수 있는 편리한 방사선량측정 방법으로 기대된다.

중심단어: 몬테카를로방법, 선량측정법, 콘빔시티, 광자극발광선량계