ORGAN ABSORBED DOSE AND THE EFFECTIVE DOSE CALCULATED USING COMPUTATIONAL ANATOMICAL PHANTOMS FOR DEDICATED CONE BEAM ORAL AND MAXILLOFACIAL CT[*]

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Abstract

This study reports the Monte Carlo dose estimates for dedicated cone beam computed tomography (CBCT) of the oral and maxillofacial region. The Monte Carlo simulation model was established for two commercial CBCT systems. Organ absorbed dose and effective dose were calculated for four computational phantoms of the adult human head and neck undergoing typical oral examinations. Dose results are normalized with the product of the operating tube current and the exposure time and are tabulated in detail for comparison purposes. The approach of Monte Carlo modeling with computational anatomical phantoms is efficient and can be adopted for detailed dose evaluation even beyond current system designs.

1. INTRODUCTION

Cone beam computed tomography (CBCT) with dedicated imaging systems [1] is increasingly used in diagnostic radiology and image-guided surgery of the oral and maxillofacial region. While offering a relatively easy and convenient access to three-dimensional visualization, it has also drawn a great concern regarding the radiation risk, especially in comparison to two-dimensional radiography as well as to conventional computed tomography (CT). Experimental dose determination mainly relies on the use of anthropomorphic phantoms loaded with thermoluminescent dosimeters, a task which is cost-prohibitive, labor-intensive and assocatiated with high uncertainty in most cases. This study makes use of a state-of-the-art Monte Carlo modeling approach with computational anatomical phantoms for dose calculation [2]. The obtained dose estimates are presented in detail for comparison purposes.

2. MATERIALS AND METHODS

2.1. CBCT systems

The 3D Accuitomo 170 (J. Morita, Japan) system and the Scanora 3D (Soredex-PaloDEx, Finland) system were chosen for investigation. Both systems use flat panel detector technology. The Accuitomo provides a number of imaging fields of view (FOV), ranging from 60×60 mm to 170×120 mm, denoted as diameter by height. The Scanora provides three FOVs: 60×60 mm (small), 100×75 mm (medium) and 145×75 mm (large). The operational tube potential is adjustable from 60 to 90 kV with the Accuitomo and is fixed to 90 kV with the Scanora. The range of operational tube currents is 1.0-10.0 mA with the Accuitomo and 4.0-12.5 mA with the Scanora.

2.2. Computational anatomical phantoms

Computational anatomical phantoms were used to represent a patient undergoing a CBCT examination. The head and neck part of four voxel-based phantoms were utilized in our investigation.

The ICRP reference phantoms for adult male and female [3]. The voxel resolution is 2.137×2.137×8.0 mm^3 for the male, and 1.775×1.775×4.84 mm^3 for the female phantom, denoted as

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coronal by sagittal by vertical direction. The total mass of the head and neck is ~5700 g and ~4000 g for the male and female phantom, respectively.

The Zubal adult male phantom [4]. The voxel resolution was adapted to $1.5 \times 1.5 \times 5.0$ mm^3 in this study. The total mass of the head and neck is ~6100 g.

The VCH adult male phantom [5]. The voxel resolution is $2.0 \times 2.0 \times 2.0$ mm^3. The total mass of the head and neck is ~4300 g.

2.3. Monte Carlo technique

A Monte Carlo simulation model had been established using the BEAMnrc/EGSnrc code system [6,7]. The simulation framework includes X ray generation, filtration, collimation and an accurately characterized beam quality of the delivered radiation field, as well as the rotational cone beam image acquisition geometry, based on the system specifications provided by the manufacturers. Dose calculation was realized by registering the energy deposition in each pre-defined region of interest (ROI), in this case organ, while tracking the radiation transport of X rays through the voxel phantoms. Greater details of the simulation technique can be found in [8].

TABLE I. ABSORBED ORGAN DOSES (μGy mAs^{-1}) FOR SELECTED FOVS OF THE ACCUITOMO AT 90 KV

Organ	ICRP Ref. Male			ICRP Ref. Female		
	170×120	100×100	60×60	170×120	100×100	60×60
Bone	106.82	58.02	23.22	146.34	86.90	33.54
Brain	16.04	3.01	0.69	31.82	7.86	1.52
Extrathoracic tissue	57.65	42.24	7.82	63.38	63.76	28.61
Eyes	63.00	5.71	1.18	87.70	93.11	4.01
Lymphatic nodes	63.89	58.51	25.98	69.57	53.98	31.93
Muscle	56.95	45.24	19.32	65.89	50.42	26.67
Oral mucosa	50.44	51.11	30.25	61.78	65.02	42.75
Red bone marrow	27.21	16.89	7.58	36.43	20.85	7.81
Salivary glands	74.51	51.57	24.59	72.18	60.20	40.82
Skin	35.18	23.36	9.27	49.21	31.97	14.59
Teeth	248.77	277.29	159.56	246.75	267.87	167.48
Tongue	53.35	55.10	37.77	54.00	54.05	37.12
Organ	Zubal			VCH		
	170×120	100×100	60×60	170×120	100×100	60×60
Bone	102.78	68.96	25.59	160.27	91.60	30.79
Brain	17.52	5.85	0.92	37.53	10.53	2.71
Extrathoracic tissue	45.61	40.30	22.00	56.81	54.45	13.83
Eyes	81.89	31.34	1.64	87.71	12.14	1.89
Lymphatic nodes	53.97	32.88	9.00	36.49	26.77	10.10
Muscle	46.11	35.42	17.96	56.11	41.39	20.88
Oral mucosa				76.08	89.24	60.48
Red bone marrow	26.62	17.81	6.57	38.51	21.97	7.27
Salivary glands				77.10	67.86	47.13
Skin	36.63	27.33	10.94	48.59	34.48	13.34
Teeth	240.18	256.70	166.59	302.66	353.06	211.95
Tongue	50.81	50.02	37.36	64.11	68.41	47.06

TABLE II. ABSORBED ORGAN DOSES (μGy mAs^{-1}) CALCULATED WITH THE SCANORA

Organ	ICRP Ref. Male			ICRP Ref. Female		
	145×75	100×75	60×60	145×75	100×75	60×60
Bone	68.30	33.60	23.78	80.23	52.24	34.36
Brain	10.14	1.04	0.72	8.52	2.68	1.56

Extrathoracic tissue	46.41	17.73	9.44	57.43	53.20	30.08
Eyes	33.64	1.67	1.25	70.70	8.62	4.54
Lymphatic nodes	25.79	42.94	26.99	51.83	45.26	28.33
Muscle	28.72	31.41	18.77	49.16	39.19	24.70
Oral mucosa	41.25	39.09	34.00	50.35	60.98	50.53
Red bone marrow	16.54	11.63	8.73	20.66	13.32	8.83
Salivary glands	49.24	31.52	19.79	60.49	51.51	29.41
Skin	21.14	13.99	8.23	29.06	20.05	12.44
Teeth	243.26	191.49	178.51	250.28	255.65	228.42
Tongue	39.16	51.36	48.19	50.73	55.39	43.50

Organ	Zubal			VCH		
	145×75	100×75	60×60	145×75	100×75	60×60
Bone	65.31	37.26	26.16	97.19	44.88	29.52
Brain	9.59	1.39	0.89	18.36	3.27	2.47
Extrathoracic tissue	15.44	41.56	27.73	45.93	20.08	15.31
Eyes	37.27	2.75	1.76	27.17	2.50	2.06
Lymphatic nodes	26.46	16.86	12.70	21.55	16.86	9.64
Muscle	25.91	27.23	17.50	28.33	34.06	19.81
Oral mucosa				36.57	80.06	66.26
Red bone marrow	17.62	10.09	7.10	24.42	11.25	7.40
Salivary glands				49.60	59.16	40.82
Skin	21.13	16.83	10.32	28.30	20.42	12.18
Teeth	218.53	237.87	208.62	246.68	313.79	262.98
Tongue	37.87	45.18	43.77	50.03	65.12	57.11

TABLE III. THE EFFECTIVE DOSES (μSv mAs^{-1}) ASSOCIATED WITH TABLES I AND II.

	Accuitomo					Scanora			
FOV	Ref. male	Ref. female	Zubal	VCH	FOV	Ref. male	Ref. female	Zubal	VCH
170×120	2.496	2.898	1.870	3.182	145×75	1.757	2.072	1.089	1.944
100×100	1.780	2.267	1.463	2.584	100×75	1.099	1.842	1.171	1.797
60×60	0.767	1.237	0.792	1.346	60×60	0.785	1.219	0.921	1.346

3.   RESULTS

In the simulation, we mimicked typical clinical protocols and positions of the FOV as close as possible. For the Accuitomo, simulations included 170×120 mm and for Scanora 145×75 mm, representing the acquisitions of the entire dentomaxillofacial or craniomaxillofacial region; the medium FOVs, e.g., Accuitomo 100×100 mm and Scanora 100×75 mm, were selected for either the maxillofacial region or the oral region; small FOVs, e.g., Accuitomo and Scanora 60×60 mm, were simulated for specific local sites. The calculated organ dose estimates were normalized against the product of the operating tube current and the effective exposure time, i.e., provided in units of μGy mAs^{-1}. An overall statistical uncertainty of <5%, in terms of relative standard deviation, was achieved. The so-called 3-factor approach was adopted for skeletal dosimetry [9]. The effective doses were derived according to [10], where appropriate fractioning, splitting and transferring of the tissue weighting factors were made with respect to the organs available in the phantoms. Those for organs that do not belong to the head and neck anatomy was set to be zero, while those for partially presented organs was fractioned by the corresponding organ mass in the entire body. The extrathoracic tissue was represented by the pharynx in the Zubal phantom and included the entire larynx, pharynx and nasal vestibule in the VCH phantom. The oral mucosa of the VCH phantom was represented by the entire gum. The tongue was used as a surrogate for the salivary glands in the Zubal phantom. The lymphatic nodes, which were neither available in the Zubal nor in the VCH phantom, were substituted by the fat tissue. The weighting factor for the oral mucosa was split and evenly transferred to all the

organs in the remainder for the Zubal phantom. The calculated organ absorbed doses for selected FOVs of the Accuitomo and the Scanora under a tube potential of 90 kV are presented in Tables I and II, respectively. The corresponding effective doses are presented in Table III.

4.   DISCUSSION AND CONCLUSION

It can be observed that the dedicated CBCT of the oral and maxillofacial region is associated with a large dose range. Owing to its accuracy in describing the physical and geometric characteristics of CBCT as well as its flexibility in configuring the exposure setting, the Monte Carlo modeling approach is more efficient than experimental measurements for dose determination of the dedicated oral and maxillofacial CBCT. The simulation model can be easily implemented to different CBCT systems. It has a potential of systematically evaluating various dose influencing factors and also a potential of predicting the dose distribution beyond the range of parameter setting provided by the current system. More specific computational anatomical phantoms can be used in dose estimation for different patients or human groups. Validated simulation frameworks may become powerful tools in patient dosimetry in the future.

REFERENCES

[1]   MIRACLE, A.C., MUKHERJI, S.K., Conebeam CT of the head and neck, part 2: clinical applications, Am. J. Neuroradiol. **30** (2009) 1285-92.

[2]   ZAIDI, H., XU, X.G., Computational anthropomorphic models of the human anatomy: the path to realistic Monte Carlo modeling in radiological sciences, Annu. Rev. Biomed. Eng. **9** (2007) 471-500.

[3]   INTERNATIONAL COMMISSION ON RADIOLOGICAL PROTECTION, Adult reference computational phantoms, ICRP Publication 110, Ann. ICRP 39, Pergamon Press, Oxford (2009).

[4]   ZUBAL, I. G., et al., Computerized three-dimensional segmented human anatomy, Med. Phys. **21** (1994) 299-302.

[5]   ZHANG, G., et al., The development and application of the visible Chinese human model for Monte Carlo dose calculations, Health Phys. **94** (2008) 118-25.

[6]   ROGERS, D.W.O., et al., BEAMnrc users manual, NRCC Report PIRS-0509(A)revK, National Research Council, Ottawa (2009).

[7]   KAWRAKOW, I., et al., The EGSnrc code system: Monte Carlo simulation of electron and photon transport, NRCC Report PIRS-701, National Research Council, Ottawa (2010).

[8]   ZHANG, G., et al., Development and validation of a hybrid simulation technique for cone beam CT: application to an oral imaging system, Phys. Med. Biol. **56** (2011) 5823-43.

[9]   ZANKL, M., et al., Organ dose conversion coefficients for external photon irradiation of male and female voxel models, Phys. Med. Biol. **47** (2002) 2367-85.

[10]   INTERNATIONAL COMMISSION ON RADIOLOGICAL PROTECTION, The 2007 recommendations of the International Commission on Radiological Protection, ICRP Publication 103, Ann. ICRP 37, Pergamon Press, Oxford (2007),