Vol. 106 No. 1 July 2008

Oral Surgery, Oral Medicine, Oral Pathology, Oral Radiology, and Endodontology

ORAL AND MAXILLOFACIAL RADIOLOGY Editor: Allan G. Farman

Comparative dosimetry of dental CBCT devices and 64-slice CT for oral and maxillofacial radiology

John B. Ludlow, DDS, MS, FDS RCSEd,[a] and Marija Ivanovic, PhD,[b] Chapel Hill, North Carolina
UNIVERSITY OF NORTH CAROLINA

Objectives. This study compares 2 measures of effective dose, E_{1990} and E_{2007}, for 8 dentoalveolar and maxillofacial cone-beam computerized tomography (CBCT) units and a 64-slice multidetector CT (MDCT) unit.
Study design. Average tissue-absorbed dose, equivalent dose, and effective dose were calculated using thermoluminescent dosimeter chips in a radiation analog dosimetry phantom. Effective doses were derived using 1990 and the superseding 2007 International Commission on Radiological Protection (ICRP) recommendations.
Results. Large-field of view (FOV) CBCT E_{2007} ranged from 68 to 1,073 μSv. Medium-FOV CBCT E_{2007} ranged from 69 to 560 μSv, whereas a similar-FOV MDCT produced 860 μSv. The E_{2007} calculations were 23% to 224% greater than E_{1990}.
Conclusions. The 2007 recommendations of the ICRP, which include salivary glands, extrathoracic region, and oral mucosa in the calculation of effective dose, result in an upward reassessment of fatal cancer risk from oral and maxillofacial radiographic examinations. Dental CBCT can be recommended as a dose-sparing technique in comparison with alternative medical CT scans for common oral and maxillofacial radiographic imaging tasks. **(Oral Surg Oral Med Oral Pathol Oral Radiol Endod 2008;106:106-14)**

Three-dimensional (3D) diagnostic imaging of the jaws has been of interest from the introduction of computerized tomography (CT) as a clinical tool. Because of relatively high cost, high dose, and availability limited to hospitals and medical radiology practices, use of this technology in dentistry has been relegated to investigation of neoplasia or significant developmental disturbance. With the introduction of relatively low-cost and low-dose[1-4] cone-beam CT (CBCT) units dedicated to maxillofacial imaging, interest in using CT for an increasing number of dental procedures has increased dramatically. The number of maxillofacial CBCT units has been increasing rapidly, and there are 9 commercially available units in the U.S. market as of this writing, with several other vendors poised to enter the market. A number of diagnostic tasks unique to dentistry are driving this development. Planning of implant placement to replace teeth, secure dentures, or anchor orthodontic appliances is one of the most frequent applications for 3D investigations of the jaws. Orthodontic and orthognathic surgical planning for patients with significant facial asymmetry has also been increasingly applied to 3D volumes. One of the elements driving marketing of CBCT units to dentists is the potential for replacing alternative imaging modalities such as panoramic radiography and cephalometric radiography, with CBCT volumes specifically reconstructed to simulate or supplant those conventional modalities. Although the idea of replacing multiple dental radiographic units with a single universal imaging device is seductive, concern has been expressed about cost to the patient in terms of dollars and dose from a "one-size-fits-all" approach to diagnostic imaging.[5]

The possibility of a pituitary or thyroid link in the risk of low-birth-weight infants due to maternal exposures to low levels of dental X-ray is a recent example of a continuing scrutiny of potential radiation hazards

[a]Professor, Department of Diagnostic Sciences and General Dentistry, University of North Carolina School of Dentistry.
[b]Department of Radiology, University of North Carolina Hospitals.
Received for publication Feb 10, 2008; returned for revision Mar 11, 2008; accepted for publication Mar 13, 2008.
1079-2104/$ - see front matter

doi:10.1016/j.tripleo.2008.03.018

Table I. Technical factors for CBCT and MDCT imaging of maxillofacial areas

Unit and technique	*Image detector*	*Rotation*	*Basis images*	*Scan time (s)*	*mA*	*mAs*	*kV*	*Scan width (cm)*	*Scan height (cm)*	*Voxel size (mm)*
Large–field of view scans										
NewTom 3G large FOV	Image intensifier	360°	360	36	1.1-2.0	8.09	110	19	19	0.4
CB Mercuray facial mode maximum quality	Image intensifier	360°	288	10	15	150	120	19	19	0.4
CB Mercuray facial mode standard quality	Image intensifier	360°	288	10	10	100	100	19	19	0.4
Next Generation i-CAT portrait mode	CsI FPD	360°	300 (309)†	8.9	5	19	120	23.2	17	0.4
Ilumina standard	GdOS FPD	360°	301-601	20	1	20	120	19	19	0.4
Ilumina ultra	GdOS FPD	360°	301-601	40	3.8	152	120	19	19	0.1-0.4
Medium–field of view scans										
CB Mercuray panoramic mode	Image Intensifier	360°	288	10	15	150	120	15	15	0.3
Classic i-CAT standard	CsI FPD	360°	300 (309)†	20	5	19	120	16	13	0.25-0.4
Next Generation i-CAT landscape mode	CsI FPD	360°	300 (309)†	8.9	5	19	120	17	13	0.25-0.4
Galileos default	Image intensifier	210°	200	14	5	21	85	15	15	0.15-0.3
Galileos maximum	Image intensifier	210°	200	14	7	42	85	15	15	0.15-0.3
Somaton	64-slice detector	6 × 360°	spiral slices	1	90	90*	120	body width	12	0.6
Somaton w/ CARE Dose 4D	64-slice detector	6 × 360°	spiral slices	1	46-84	*	120	body width	12	0.6
Small field of view scans										
CB Mercuray I mode	Image intensifier	360°	288	10	15	150	120	10	10	0.2
Promax 3D small adult	CMOS FPD	191°	300	18	12	72	84	8	8	0.16
Promax 3D large adult	CMOS FPD	191°	300	18	16	96	84	8	8	0.16
Prexion 3D standard	CsI FPD	360°	512	19	4	76	90	8.1	7.6	0.08
Prexion 3D high res	CsI FPD	2 × 360°	1024	37	4	148	90	8.1	7.6	0.08

CBCT, Cone-beam comuterized tomography; *MDCT*, multidetector computerized tomography; *FOV*, field of view.
*Listed mAs is the effective mAs = mAs/Pitch factor; pitch factor for dental scans is 0.9; scan time listed is time for 1 rotation. The total scan time depends on length of scan.
†Original basis images; initial frames are discarded until X-ray output reaches peak.

from conventional dental diagnostic imaging.[6] Newly adopted recommendations of the International Commission on Radiological Protection (ICRP) provide revision of tissue-weighting factors and inclusion of salivary glands as a weighted tissue. These changes will likely result in an upward reassessment of effective dose from oral and maxillofacial radiographic examinations.[7]

Because X-ray risks are cumulative it is imperative that strategies for dose reduction, including the choice of radiographic unit, be considered in examining all patients. Reassessment of the radiobiologic risk of maxillofacial examinations using the 2007 recommendations of the ICRP has not been previously reported. The present study provides comparative measurements of effective dose from several dentoalveolar and maxillofacial CBCT units and a 64-slice multiple-row-detector CT (MDCT) unit. Average tissue-absorbed dose, weighted (equivalent) radiation dose, and effective dose are calculated for the anatomy of the head and neck area. Effective doses are reported using 1990 ICRP guidelines[8] and the revised 2007 recommendations.[7]

MATERIALS AND METHODS

Doses for the following CBCT units were investigated: NewTom 3G (QR, Verona, Italy); CB Mercuray (Hitachi Medical of America, Twinsburg, OH); Promax 3D (Planmeca OY, Helsinki, Finnland); Prexion 3D (Terarecon, San Mateo, CA); Galileos (Sirona, Charlotte, NC); Classic i-CAT (Imaging Sciences International, Hatfield, PA); Next Generation i-CAT (Imaging Sciences International); and Iluma (Imtec Imaging, Ardmore, OK). Dose for the 64-slice MDCT was measured using the Somatom Sensation 32-row/64-slice configuration (Siemens Medical Solutions USA, Malvern, PA). X-Ray parameters of kV and mA were set to provide "default" scanning options. Additional exposures were made at higher or lower exposures when these options were available. In the case of the iCAT Classic, an older unit manufactured in 2003, and a new unit manufactured in 2007 were evaluated and disometry results were averaged. Factors used for each device can be seen in Table I. Examinations are grouped by field of view (FOV) size. A small FOV was considered to be a spherical diameter or cylinder height of 10 cm or less. This FOV size is useful for imaging

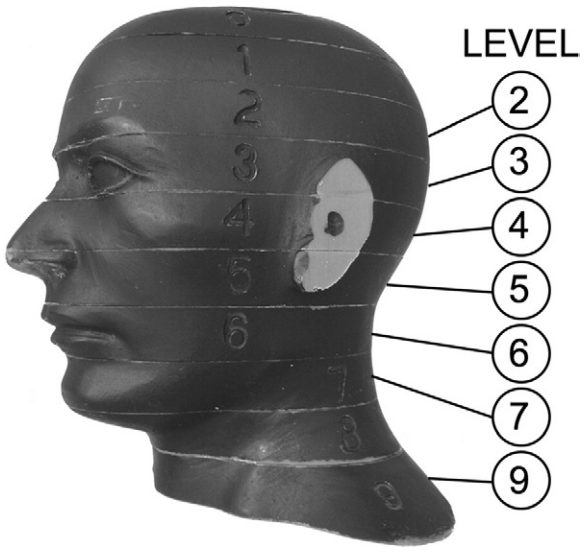

Fig. 1. Adult skull and tissue-equivalent phantom (RANDO). Levels correspond to TLD dosimeter sites identified in Table 2.

Table II. Locations of TLD chips in RANDO phantom

Phantom location	*TLD ID*
Calvarium anterior (2)	1
Calvarium left (2)	2
Calvarium posterior (2)	3
Midbrain (2)	4
Pituitary (3)	5
Right orbit (4)	6
Left orbit (4)	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
Left back of neck (7)	16
Right mandible body (7)	17
Left mandible body (7)	18
Right submandibular gland (7)	19
Left submandibular gland (7)	20
Center sublingual gland (7)	21
Midline thyroid (9)	22
Thyroid surface—left (9)	23
Esophagus (9)	24

TLD, Thermoluminescent dosimeter; *RANDO*, radiation analog dosimetry.

most of one or both arches, but cannot capture the full anatomy of both jaws. Medium FOVs include spherical volume diameters or cylinder heights greater than 10 cm up to 15 cm. These volumes may capture the dentition and TMJs for most patients but will not typically capture the soft tissue contours of the chin and nose at the same time and are thus not optimal for orthodontic analysis. Large FOVs include spherical volume diameters or cylinder heights greater than 15 cm which can capture the soft tissue profile of the nose and chin and complete maxillofacial complex.

Volume CT dose index ($CTDI_{vol}$) was measured on the MDCT with a Radcal MDH model 1515 electrometer using a model 10×9-3CT pencil ionization chamber (Radcal Corporation, Monrovia, CA) and a 16-cm-diameter polymethyl methacrylate (PMMA) cylinder. The $CTDI_{vol}$ is the weighted average of CTDI measurements at the center and at the 12 o'clock location of the phantom divided by the pitch.[9] Because CTDI dose calculations are less accurate when calculated with cone-beam image acquisition,[10-12] dosimetry was also acquired for CT and CBCT units using an adult male skull and tissue-equivalent phantom (radiation analog dosimetry [RANDO] system; Nuclear Associates, Hicksville, NY) (Fig. 1). Thermoluminescent dosimeter chips (TLDs) were used to record the distribution of the absorbed radiation dose at selected locations in the head and neck region of this phantom. The 24 phantom sites measured in this study are listed in Table II. During scanning, the phantom was oriented with the occlusal plane parallel to the scan rotation plane. Three scans for each technique were used to provide a more reliable measure of radiation in the dosimeters. The TLD doses were divided by the number of scans to determine the "exposure per scan" for each dosimeter.

Precalibrated 3 × 3 × 1 mm TLD 100 lithium fluoride chips were supplied and analyzed by Landauer, Inc. (Glenwood, IL). Doses from TLDs at different positions within a tissue or organ were averaged to express the average tissue-absorbed dose in micrograys (μGy). The products of these values and the percentage of a tissue or organ irradiated (Table III) in a radiographic examination were used to calculate the equivalent dose (H_T) in microsieverts (μSv).[7]

For bone marrow, the equivalent dose to the whole-body bone marrow was calculated using the summation of the individual equivalent doses to the calvarium, the mandible, and the cervical spine. The determination of these equivalent doses is based on the distribution of active bone marrow throughout the adult body: the mandible contains 1.3%, the calvarium 11.8%, and the cervical spine 3.4%.[13] Following the technique of Underhill et al., 3 locations within the calvarium were averaged to determine calvarial dose.[14] For bone, a correction factor based on experimentally determined mass energy attenuation coefficients for bone and muscle irradiated with monoenergetic photons was applied.[15,16] An effective beam energy estimated to be two-thirds of the peak beam energy for each X-ray unit

Table III. Estimated percentage of tissue irradiated and TLDs used to calculate mean absorbed dose to a tissue or organ

	Fraction irradiated	*TLD ID (see Table I)*
Bone marrow	16.5%	
Mandible	1.3%	13, 14, 17, 18
Calvarium		1, 2, 3
Cervical spine	3.4%	15
Thyroid	100%	22, 23
Esophagus	10%	24
Skin	5%	8, 9, 10, 16
Bone surface*	16.5%	
Mandible	1.3%	13, 14, 17, 18
Calvarium	11.8%	1, 2, 3
Cervical spine	3.4%	15
Salivary glands	100%	
Parotid	100%	11, 12
Submandibular	100%	19, 20
Sublingual	100%	21
Brain‡	100%	4, 5
Remainder		
Brain†	100%	4, 5
Lymphatic nodes‡	5%	11-15, 17-22, 24
Muscle†‡	5%	11-15, 17-22, 24
Extrathoracic airway‡	100%	6, 7, 11-15, 17-22, 24
Oral mucosa‡	100%	11-14, 17-21
Pituitary	100%	5
Eyes	100%	6, 7, 8, 9

*Bone surface dose = bone marrow dose × bone/muscle mass energy absorption coefficient ratio (MEACR). MEACR = −0.0618 × 2/3 kV peak + 6.9406 using data taken from National Bureau of Standards handbook no. 85.[15]
†1990 recommendations of the International Commission on Radiological Protection (ICRP).[8]
‡2007 recommendations of the ICRP.[7]

Table IV. Tissue-weighting factors for calculation of effective dose—ICRP 1990[8] and 2007[7] recommendations.

Tissue	*1990* w_T	*2007* w_T
Bone marrow	0.12	0.12
Breast	0.05	0.12
Colon	0.12	0.12
Lung	0.12	0.12
Stomach	0.12	0.12
Bladder	0.05	0.04
Esophagus	0.05	0.04
Gonads	0.20	0.08
Liver	0.05	0.04
Thyroid	0.05	0.04
Bone surface	0.01	0.01
Brain	remainder	0.01
Salivary glands	—	0.01
Skin	0.01	0.01
Remainder tissues	0.05*	0.12†

ICRP, International Commission on Radiological Protection.
*Adrenals, *brain*, upper large intestine, small intestine, kidney, *muscle*, pancreas, spleen, thymus, uterus. Italicized text represents remainder tissues used for calculation of maxillofacial dose.
†Adrenals, *extrathoracic region*, gall bladder, heart, kidneys, *lymphatic nodes*, *muscle*, *oral mucosa*, pancreas, prostate, small intestine, spleen, thymus, and uterus/cervix. Italicized text represents remainder tissues used for calculation of maxillofacial dose.

was used to determine bone/muscle attenuation ratios. A linear fit ($R^2 = 0.996$) of ratios from 40 to 80 kV produced the following equation: bone/muscle attenuation ratio = −0.0618 × kV peak × 2/3 + 6.9406. Values calculated from this equation ranged from 3.5 at 56 kV (84 kV peak) to 2.0 at 80 kV (120 kV peak).

The proportion of skin surface area in the head and neck region directly exposed by each technique is estimated as 5% of the total body to calculate weighted radiation dose to the skin following the procedure of Ludlow et al.[1] Similarly, muscle and lymphatic node exposures are estimated to represent 5% of the total body complement for these tissues. The proportion of the esophageal tract that is exposed was set at 10%.

Effective dose (E) is a widely used 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 μSv, is calculated using the equation: $E = \Sigma w_T \times H_T$, where E is the product of the tissue weighting factor (w_T), which represents the relative contribution of that organ or tissue to the overall risk, and the equivalent dose H_T.[7] The whole-body risk is found by the summation of the weighted equivalent doses to all tissues or organs exposed. Both the earlier 1990 ICRP tissue-weighting factors and the new 2007 weighting factors found in Table IV were used to calculate effective dose.[7,8]

The 1990 weighting factors were assigned to 12 organs or tissues and a group of remainder organs for purposes of calculating total E (Table IV). Of the individually weighted tissues or organs, only bone marrow, esophagus, thyroid, bone surface, and skin doses are included in this study. Of the 10 organs making up the remainder category, only brain and muscle are included. The other individual or remainder organs are not directly exposed in the protocols used in this study. Although an assumption of no dose may underestimate actual exposure to these organs, the impact on total E is negligible. A report of a C-arm CBCT exposure of a 16 cm cylindrical head phantom found that the air dose 35 cm from the isocenter of the phantom was reduced to 2.6% of the direct exposure.[15,16] Attenuation by tissues in the path of the scatter further reduce this small percentage.

Table V. Equivalent dose (μSv) to tissues/organs in the head and neck from CBCT and MDCT examinations

								Remainder tissues/organs				
Values from RANDO phantom	*Bone Marrow*	*Thyroid*	*Esophagus*	*Skin*	*Bone surface*	*Salivary glands*	*Brain**	*Brain†*	*Lymphatic nodes**	*Extrathoracic region**	*Muscle*†*	*Oral mucosa**
NewTom 3G large FOV[4]	125	333	57	62	581	956	700	700	42	826	42	915
CB Mercuray maximum quality[4]	1,542	10,042	622	788	7,153	11,833	9,275	9,275	536	10,633	536	11,226
CB Mercuray F FOV standard quality[4]	692	6,333	393	389	3,211	5,467	3,967	3,967	256	5,036	256	5,211
Next Generation i-CAT portrait mode	147	183	33	52	294	1250	950	950	54	1083	54	1226
CB Mercuray P FOV[4]	940	1,700	177	641	4,360	10,561	5,933	5,933	430	8,736	430	10,111
Classic i-CAT standard FOV	95	267	30	54	149	1,450	567	567	61	1,224	61	1,422
Next Generation i-CAT landscape mode‡	105	283	45	82	211	1836	808	808	76	1537	76	1776
Iluma standard	161	350	50	82	745	1,661	1,267	1,267	72	1,455	72	1,630
Iluma ultra	834	1,733	233	421	3,869	8,400	6,267	6,267	363	7,433	363	8,289
Galileos default exposure	82	233	37	40	382	1,606	267	267	68	1,283	68	1,556
Galileos maximum exposure	150	450	47	77	696	2,900	467	467	125	2,362	125	2,896
Somatom 64 MDCT	1,031	3,700	1,560	619	4,785	15,300	7,100	7,100	696	13,514	696	14,878
Somatom 64 MDCT w/ CARE Dose 4D	679	2,350	740	501	3,151	8,667	5,750	5,750	408	8,357	408	8,789
CB Mercuray I FOV maxillary arch[4]	466	1,300	110	344	2,161	9,006	2,950	2,950	383	7,769	383	9,078
Promax 3D small adult	468	1,267	120	339	2,170	12,939	600	600	543	9,631	543	13,285
Promax 3D large adult	592	1,783	207	382	2,747	17,539	800	800	719	12,731	719	17,581
PreXion 3D standard	164	683	53	135	760	4,761	383	383	192	3,805	192	4,704
PreXion 3D high res	325	1,800	133	264	1,508	9,372	783	783	375	7,183	375	9,085
Estimates based on $CTDI_{vol}$ data												
Somatom 64 MDCT	597	0	1,270	635	2,770	12,700	0	0	635	12,700	635	12,700
Somatom 64 MDCT w/ CARE Dose 4D	383	0	728	520	1,776	7,700	0	0	389	8,352	389	7,793

$CTDI_{vol}$, Volume CT dose index; other abbreviations as in Tables I and II.
*International Commission on Radiological Protection (ICRP) 2007.
†ICRP 1990.
‡Average of 2 dosimeter runs.
[4]Previously published data.

Tissue-weighting factors for 2007 increase the number of independently weighted tissues by 2 and expand the number of remainder tissues to 14 (Table IV). Of the new independent tissues, both brain and salivary gland tissues were used in the present study's calculations. The 2007 remainder tissues directly exposed in maxillofacial CBCT exams include oral mucosa, lymphatic nodes, muscle, and the extrathoracic region. A body fraction of 100% was used in the calculation of dose to oral mucosa and extrathoracic region tissues for the scanning protocols used in the present study. Because the uterus/cervix is present only in females and the prostate only in males, the number used in the weighted averaging of remainder tissues is 13.

The ICRP Publication No. 60 suggested that radiation detriment could be calculated from E.[8] Radiation detriment was defined in this case as the total harm to an exposed population and their descendants. Detriment includes the weighted probabilities of fatal and nonfatal cancer, hereditary effects, and the relative length of life lost. The coefficient assigned to these combined effects was 7.3×10^{-2} Sv^{-1}. Because of great uncertainty on the form of the dose response below 0.1 Sv, the ICRP currently suggests that no specific judgment on low dose risk of noncancer diseases is possible. Therefore, a risk coefficient of 5.5×10^{-2} Sv^{-1} based on cancer risk alone was used for 2007 risk estimates (Annex A).[7]

RESULTS

Table V provides equivalent doses for the weighted tissues and organs that receive direct exposure during maxillofacial imaging. Two dosimeter runs on the same Next Generation iCAT unit in landscape mode were available. The mean dosimeter exposure for each run was found to vary by less than 2%. An average of the values from the 2 runs is presented in table V. It is noteworthy that salivary gland contribution to effective doses range from 1 mSv to more than 17 mSv depending on the radiographic unit and technical factors of the examination. Similar patterns are seen for oral mucosa and the extrathoracic tissues. The differences between

Table VI. Effective dose from dento-alveolar and maxillofacial radiographic examinations for CBCT and MDCT devices: Comparison of ICRP 1990 and 2007 calculations

Technique	*Effective dose, μSv, ICRP 1990 tissue weights*	*Effective dose, μSv, ICRP 2007 tissue weights*	*Change in effective dose, 1990-2007*
Large FOV			
NewTom 3G large FOV[4]	42	68	62%
CB Mercuray facial FOV maximum quality[4]	806	1073	33%
CB Mercuray facial FOV standard quality[4]	464	569	23%
Next Generation i-CAT portrait mode	37	74	100%
Iluma standard	50	98	97%
Iluma ultra	252	498	97%
Average			61%
Medium FOV			
CB Mercuray panoramic FOV[4]	264	560	112%
Classic i-CAT standard scan	29	69	137%
Next Generation i-CAT landscape mode	36	87	139%
Galileos default exposure	28	70	148%
Galileos maximum exposure	52	128	148%
Somaton 64 MDCT	453	860	90%
Somaton 64 MDCT w/ CARE Dose 4D	285	534	87%
Average			123%
Small FOV			
CB Mercuray I FOV maxillary[4]	156	407	161%
Promax 3D small adult	151	488	224%
Promax 3D large adult	203	652	222%
PreXion 3D standard exposure	66	189	187%
PreXion 3D high resolution	154	388	151%
Average			189%

ICRP, International Commission on Radiological Protection.
[4]Previously published data.

organ (tissue) dose estimated from $CTDI_{vol}$ and TLD measurements ranged from −30% to +30% for organs (tissues) that were in the direct beam. For organs that were in the spiral over-scan range (adjacent to the predefined scanned region), the differences were slightly larger. The doses to the organs outside the direct beam and spiral over-scan were not calculated. The TLD values served as the reference standard to calculate the differences in dose. Effective doses estimated from $CTDI_{vol}$ were underestimated by 62% using the ICRP 1990 tissue-weighting factors (E_{CTDI} = 172 μSv; E_{TLD} = 453 μSv for the dental scan protocol) and by 38% using the ICRP 2007 tissue weighting factors (E_{CTDI} = 530 μSv; E_{TLD} = 860 μSv). Table VI compares effective doses calculated with the 1990 and 2007 tissue-weighting factors. Effective dose calculations using the 2007 ICRP recommendations increased for all radiographic examinations compared with the 1990 calculations. Individual results for the older iCAT Classic unit were E_{1990} 65.5 and E_{2007} 135. For the newer unit they were E_{1990} 29.3 μSv and E_{2007} 68.9 μSv. These results were averaged for Tables VI and VII. Table VII depicts alternative means of comparing effective doses from the different units and techniques. These include doses as multiples of dental panoramic examinations, days of per capita background dose based on an annual full body exposure of 3 mSv, and probability of a stochastic effect (ICRP 1990) or fatal cancer (ICRP 2007).

DISCUSSION

Revision of tissue-weighting factors in the 2007 ICRP recommendations is made possible by the availability of cancer incidence data that was not available when the 1990 guidelines were published. The 1990 ICRP cancer risks were computed based on mortality data. Incidence data provides a more complete description of cancer burden than mortality data alone, particularly for cancers that have a high survival rate. Much of the cancer incidence data comes from the Life Span Study of Japanese atomic bomb survivors, which has been updated with follow-up through 1998 and corrected using DS86 bomb dosimetry. Weighted tissues and organs and revised weights in the 2007 recommendations are justified because of accumulated epidemiologic information on the tumorigenic effects of radiation that is now sufficient to make judgments necessary for estimating cancer risks. Cancer risk in salivary glands and brain were judged to be greater than that of other tissues in the remainder fraction, and each is

Table VII. Alternative comparisons of dose and risk from maxillofacial examinations using MDCT and CBCT devices: comparison of ICRP 1990 and 2007 tissue weights

Technique	*Dose as multiple of average panoramic dose,* ICRP 1990*	*Dose as multiple of typical panoramic dose,† ICRP 2007*	*Days of per capita background, ICRP 1990*	*Days of per capita background, ICRP 2007*	*Probability of x in a million stochastic effect, ICRP 1990*	*Probability of x in a million fatal cancer, ICRP 2007*
Large FOV						
NewTom 3G large FOV[11]	6	3	5	8	3	4
CB Mercuray facial FOV maximum quality[4]	124	44	98	131	59	59
CB Mercuray facial FOV standard quality[4]	71	23	56	69	34	31
Next Generation i-CAT portrait mode	6	3	4	9	3	4
Iluma standard	8	4	6	12	4	5
Iluma ultra	39	20	31	61	18	27
Medium FOV						
CB Mercuray panoramic FOV[4]	41	23	32	68	19	31
Classic i-CAT standard scan	7	4	6	12	3	6
Next Generation i-CAT landscape mode	6	4	4	11	3	5
Galileos default exposure	4	3	3	9	2	4
Galileos maximum exposure	8	5	6	16	4	7
Somatom 64 MDCT	70	35	55	105	33	47
Somatom 64 MDCT w/ CARE Dose 4D	44	22	35	65	21	29
Small FOV						
CB Mercuray I FOV maxillary[4]	24	17	19	50	11	22
Promax 3D small adult	23	20	18	59	11	27
Promax 3D large adult	31	27	25	79	15	36
PreXion 3D standard exposure	10	8	8	23	5	10
PreXion 3D high resolution	24	16	19	47	11	21

Abbreviations as in Tables I and IV.
*6.5 μSv.
†24.5 μSv, Planmeca Promax digital panoramic device.
[4]Previously published data.

ascribed a w_T of 0.01. A w_T value for the remainder tissues of 0.12, distributed equally among 13 of 14 named tissues, provides a weight of approximately 0.009 each, which is just marginally lower than the w_T for the lowest of the named tissues.

Revision of the 1990 ICRP recommendations has gone through several iterations. A draft in 2005 proposed the addition of adipose and connective tissues and did not include oral mucosa in the remainder group of weighted tissues. In addition, that draft used a weight of 0.10 for the remainder group instead of the final factor of 0.12. The 2007 recommendations also reduce the weight for the thyroid gland and esophagus to 0.04. Reduction in the weighting of these tissues is overbalanced by the net increase of 2 weighted tissues as well as 2 organs or tissues within the remainder group that are directly exposed during maxillofacial radiologic examinations. The resulting increases in effective dose that might be expected from these changes in tissue weights are confirmed by the results of the present study. Grouped by size of the region of scanned anatomy, small-FOV examinations averaged E_{2007} increases of 189%, medium-FOV examinations averaged 123% increases, and large-FOV units averaged 69% increases. Greater increases in effective dose are seen in examinations that focus on the region where the added weighted tissues and remainder tissues are located. This effect is diluted by larger fields of view.

Discrepancies in the data may be seen in the dosimeter values for the Classic iCAT standard scan and the Next Generation iCAT Landscape mode. With x-ray exposure factors, beam sizes and mechanical distances being the same for these units, one would expect doses to be the same. Small variations in collimator adjustment, unit calibration, or phantom position within the unit may account for the approximately 23% difference seen between these units. The relatively large differences between effective dose estimated using $CTDI_{vol}$

and TLD measurements, can be accounted for in part by contributions to the TLD dose from the scanned region and doses from scatter radiation to tissues outside of the scan region that were not included in the CTDI estimates. The $CTDI_{vol}$ represents the average dose delivered to the scanned volume based on the measurements with a uniform 16-cm-diameter PMMA cylinder. The TLD dose in the RANDO phantom depends on the position of the dosimeters, skull size, and soft tissue morphology of the phantom, which simulate an actual human subject.

It is not uncommon for dentists to compare doses from different examinations in terms of multiples of panoramic exposures, one of the more common dental radiographic examinations. When this practice is compared using 1990 and 2007 ICRP tissue weights, the multiple for panoramic examinations decreases even as effective dose for CT examinations increases. This paradox is explained by the fact that panoramic scanning of the jaws involves rotational centers for scanning motions that are proximate to the ramus of the mandible for scanning of the posterior jaws and in the center of the floor of the mouth for scanning of the anterior jaws. These rotational centers coincide with the location of the parotid and submandibular glands in the posterior and sublingual gland in the anterior. While much of the scanned anatomy is only transiently exposed to radiation, anatomy at the rotational center is continuously exposed. Thus, effective doses from dental panoramic imaging will be larger than imaging procedures that produce a more uniform distribution of absorbed energy within the scanned volume.

A substantial difference in effective doses from the same unit is seen with the technique variations explored in the present study. For instance, a 38% reduction in dose is seen with the Somaton CT unit when the dental scan is run using Siemens' automatic exposure control feature, "CARE Dose 4D." An even greater difference is seen between the Iluma CBCT unit "Standard" exposure and the "Ultra" exposure. The higher Iluma dose (498 μSv) is similar to the Somaton CARE dose (534 μSv). The 500% Iluma dose increase is intended to improve signal-to-noise ratios when volumes are reconstructed with 0.1 mm voxel sizes. Unfortunately, dental radiographers have widely different levels of training and may not understand the risk implications of using higher doses to obtain image volumes. In addition, a dentist referring to an imaging center may not be aware of the differences in dose involved with image parameters that are differentiated by terms such as "standard" and "ultra." Further complicating this picture, the general dentist may not clearly communicate the diagnostic reason for the scan, or the radiographic technician who lacks the training of a technologist may not be aware of the differences in image quality or resolution that are required for such varied tasks as investigating possible vertical root fracture versus implant site treatment planning.

This issue is not unique to dentistry. Hundreds of protocols are available for the many diagnostic tasks that are associated with medical imaging. The referring clinician is often unaware of the nuances of protocol variations that are possible for the examination of a particular organ or anatomic region. It is therefore up to the radiologist and, more frequently, the radiologic technologist to make decisions about which technique factors will be used for the examination. Ideally, those factors are selected on the basis of image quality required to achieve the examination goals. Because image quality is proportional to dose, selection of image quality becomes a decision on dose and vice versa. Ideally, these decisions should be informed by the training and expertise of the radiologist who will be using the examination for diagnosis. The reality is that the majority of medical CT scans will simply follow the manufacturer's suggested scanning protocol without further consideration of the potential for dose/image quality optimization. This is because the radiologist is often not directly involved in the task of image acquisition.

A study assessing conventional CT for dental diagnosis found that a 9-fold reduction in dose could be made without significant loss of image quality.[17] Other studies have assessed dose reduction and image quality for reduced-exposure head[18] or sinus[19] examinations. Most of these studies are not comparable with either MDCT or CBCT for dental diagnosis. This is in part because of the higher resolution of dedicated dental CBCT units which utilize voxel sizes from 0.5 mm to less than 0.1 mm. Signal-to-noise also tends to increase in conjunction with increasing pixel size for a given exposure, simply owing to quantum statistics. It is not clear whether reductions in dose might be achievable for MDCT imaging for dental diagnosis. Indeed, dental diagnosis encompasses a range of tasks requiring varied levels of spatial and contrast resolution, and it is perhaps unreasonable to ask that all tasks be accomplished with a single examination using a single set of imaging parameters.

Although the 2007 ICRP tissue weights increase effective dose for maxillofacial scans, calculated fatal cancer risk from these examinations is still relatively low. The "Standard" Galileos CBCT scan results in a 4-in-a-million increased risk of fatal cancer. The "CARE Dose 4D" dental protocol for the Somaton MDCT examination results in a 7-fold increase in the risk of death to 29-in-a-million. However, the 15-fold difference in risk for similar examinations from the

different CBCT units evaluated in this study suggests a need for the application of as-low-as-reasonably-achievable principles to maxillofacial volumetric imaging. Although protocols suggested by both MDCT and CBCT manufacturers serve as a starting point and benchmark for measuring image quality and dose, development of standards for image quality and dose for the varied diagnostic tasks for which volumetric imaging is used is also needed and should be made a research priority.

Diagnostic benefit and dose detriment tradeoffs are important considerations in choices of radiographic procedures. Concern has recently been raised about increasing numbers of CT examinations in the US and the increased cancer risks, especially in children, which result from these examinations.[20] Demonstration of doses using standard protocols from recently available CBCT units and a MDCT unit with a comparison of 1990 and 2007 calculations of effective dose has not been previously reported. The estimation of fatal cancer risk arising from oral and maxillofacial CBCT or MDCT radiographic imaging has increased from 23% to 224% following the 2007 ICRP recommendations for calculating effective dose. Because confusion may arise during the transition from the use of ICRP 1990 to 2007 tissue weights, it is recommended that authors note which weights have been used when reporting effective dose (ICRP 1990 or ICRP 2007). Dental CBCT can be recommended as a dose-sparing technique compared with alternative standard medical CT scans for common oral and maxillofacial radiographic imaging tasks. Effective dose (ICRP 2007) from a standard dental protocol scan with the MDCT was from 1.5 to 12.3 times greater than comparable medium-FOV dental CBCT scans.

REFERENCES

1. Ludlow JB, Davies-Ludlow LE, Brooks SL. Dosimetry of two extraoral direct digital imaging devices: NewTom cone beam CT and Orthophos Plus DS panoramic unit. Dentomaxillofac Radiol 2003;32:229-34.
2. Mah JK, Danforth RA, Bumann A, Hatcher D. Radiation absorbed in maxillofacial imaging with a new dental computed tomography device. Oral Surg Oral Med Oral Pathol Oral Radiol Endod 2003;96:508-13.
3. Tsiklakis K, Donta C, Gavala S, Karayianni K, Kamenopoulou V, Hourdakis CJ. Dose reduction in maxillofacial imaging using low dose cone beam CT. Eur J Radiol 2005;56:413-7.
4. Ludlow JB, Brooks SL, Davies-Ludlow LE, Howerton B. Dosimetry of 3 CBCT units for oral and maxillofacial radiology. Dentomaxillofac Radiol 2006;35:219-26.
5. Farman AG. ALARA still applies. Oral Surg Oral Med Oral Pathol Oral Radiol Endod 2005;100:395-7.
6. Hujoel PP, Bollen AM, Noonan CJ, del Aguila MA. Antepartum dental radiography and infant low birth weight. JAMA 2004;291:1987-93.
7. Valentin J. The 2007 Recommendations of the International Commission on Radiological Protection. Publication 103. Ann ICRP 2007;37:1-332.
8. 1990 Recommendations of the International Commission on Radiological Protection. ICRP publication 60. Ann ICRP 1991;21:1-201.
9. Particular requirements for the safety of X-ray equipment for computed tomography. IEC publication no. 60601-2-44. Geneva: International Electrotechnical Commission (IEC) Central Office; 2002.
10. Boone JM, The trouble with CTD100. Med Phys 2007; 34:1364-71.
11. Mori S, Endo M, Nishizawa K, Tsunoo T, Aoyama T, Fujiwara H, Murase K. Enlarged longitudinal dose profiles in cone-beam CT and the need for modified dosimetry. Med Phys 2005;32:1061-9.
12. Fahrig R, Dixon R, Payne T, Morin RL, Ganguly A, Strobel N. Dose and image quality for a cone-beam C-arm CT system. Med Phys. 2006;33:4541-50.
13. White SC, Rose TC. Absorbed bone marrow dose in certain dental radiographic techniques. J Am Dent Assoc 1979;98:553-8.
14. Underhill TE, Chilvarquer I, Kimura K, Langlais RP, McDavid WD, Preece JW, et al. Radiobiologic risk estimation from dental radiology, Part I, Absorbed doses to critical organs. Oral Surg Oral Med Oral Pathol Oral Radiol Endod 1988;66:111-20.
15. Physical aspects of irradiation. NBS handbook no. 85. Washington, DC: US Government Printing Office; 1964. p. 3.
16. Daly MJ, Siewerdsen JH, Moseley DJ, Jaffray DA, Irish JC. Intraoperative cone-beam CT for guidance of head and neck surgery: assessment of dose and image quality using a C-arm prototype. Med Phys 2006;33:3767-80.
17. Rustemeyer P, Streubühr U, Suttmoeller J. Low-dose dental computed tomography: significant dose reduction without loss of image quality. Acta Radiol 2004;45:847-53.
18. Mullins ME, Lev MH, Bove P, O'Reilly CE, Saini S, Rhea JT, et al. Comparison of image quality between conventional and low-dose nonenhanced head CT. AJNR Am J Neuroradiol 2004;25:533-8.
19. Zammit-Maempel I, Chadwick CL, Willis SP. Radiation dose to the lens of eye and thyroid gland in paranasal sinus multislice CT. Br J Radiol 2003;76:418-20.
20. Brenner DJ, Hall EJ. Computed tomography—an increasing source of radiation exposure. N Engl J Med 2007;357:2277-8.

Reprint requests:

John B. Ludlow, DDS, MS, FDS RCSEd
120 Dental Office Building
UNC School of Dentistry
Chapel Hill
NC 27599-7450.
jbl@email.unc.edu