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

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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 \( \mu \)Sv. Medium-FOV CBCT \( E_{2007} \) ranged from 69 to 560 \( \mu \)Sv, whereas a similar-FOV MDCT produced 860 \( \mu \)Sv. 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\(^1\) 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.
from conventional dental diagnostic imaging. 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.

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. This 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 and the revised 2007 recommendations.

**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 (Planmec OY, Helsinki, Finland); 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 (Intec 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

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

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

CBCT, Cone-beam computerized 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.
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 (CTDỊ_{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 CTDỊ_{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 \(3 \times 3 \times 1\) 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 (\(\mu\)Gy). 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 \(\left(H_T\right)\) in microsieverts (\(\mu\)Sv).\(^7\)

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

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

*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

was used to determine bone/muscle attenuation ratios. A linear fit (R² = 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: $E = \sum w_T \times H_T$, 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 $H_T$. 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
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 \(7.3 \times 10^{-2} \) 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 \(5.5 \times 10^{-2} \) 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 i-CAT 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

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

<table>
<thead>
<tr>
<th>Values from RANDO phantom</th>
<th>Bone</th>
<th>Remainder tissues/organs</th>
</tr>
</thead>
<tbody>
<tr>
<td>NewTom 3G large FOV(^4)</td>
<td>Bone surface</td>
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</tr>
<tr>
<td>CB Mercury maximum quality(^4)</td>
<td>Bone</td>
<td></td>
</tr>
<tr>
<td>CB Mercury F FOV standard quality(^4)</td>
<td>Bone</td>
<td></td>
</tr>
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<td>Next Generation i-CAT portrait mode</td>
<td>Bone</td>
<td></td>
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<tr>
<td>CB Mercury P FOV(^4)</td>
<td>Bone</td>
<td></td>
</tr>
<tr>
<td>Classic i-CAT standard FOV</td>
<td>Bone</td>
<td></td>
</tr>
<tr>
<td>Next Generation i-CAT landscape mode(^7)</td>
<td>Bone</td>
<td></td>
</tr>
</tbody>
</table>

| CB Mercury I FOV maxillary arch\(^8\) | Bone | | | |
| Promax 3D small adult | Bone | | | |
| Promax 3D large adult | Bone | | | |
| PreXion 3D standard | Bone | | | |
| PreXion 3D high res | Bone | | | |

| Estimates based on CTDI\(_{vol}\) data | Bone | | | |
| Somatom 64 MDCT | Bone | | | |
| Somatom 64 MDCT w/ CARE Dose 4D | Bone | | | |

| CB Mercury I FOV maxillary arch\(^8\) | Bone | | | |
| Promax 3D small adult | Bone | | | |
| Promax 3D large adult | Bone | | | |
| PreXion 3D standard | Bone | | | |
| PreXion 3D high res | Bone | | | |

| Estimates based on CTDI\(_{vol}\) data | Bone | | | |
| Somatom 64 MDCT | Bone | | | |
| Somatom 64 MDCT w/ CARE Dose 4D | Bone | | | |

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\[^4\] Previously published data.

\[^5\] Average of 2 dosimeter runs.

\[^6\] International Commission on Radiological Protection (ICRP) 2007.

\[^7\] ICRP 1990.

\[^8\] CTDI\(_{vol}\), Volume CT dose index; other abbreviations as in Tables I and II.
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 ($E_{CTDI} = 172 \mu Sv; E_{TLD} = 453 \mu Sv$ for the dental scan protocol) and by 38% using the ICRP 2007 tissue weighting factors ($E_{CTDI} = 530 \mu Sv; E_{TLD} = 860 \mu Sv$). 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 $\mu$Sv and $E_{2007}$ 68.9 $\mu$Sv. 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>
<thead>
<tr>
<th>Technique</th>
<th>Effective dose, $\mu$Sv, ICRP 1990 tissue weights</th>
<th>Effective dose, $\mu$Sv, ICRP 2007 tissue weights</th>
<th>Change in effective dose, 1990-2007</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Large FOV</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>NewTom 3G large FOV$^d$</td>
<td>42</td>
<td>68</td>
<td>62%</td>
</tr>
<tr>
<td>CB Mercuray facial FOV maximum quality$^d$</td>
<td>806</td>
<td>1073</td>
<td>33%</td>
</tr>
<tr>
<td>CB Mercuray facial FOV standard quality$^d$</td>
<td>464</td>
<td>569</td>
<td>23%</td>
</tr>
<tr>
<td>Next Generation i-CAT portrait mode</td>
<td>37</td>
<td>74</td>
<td>100%</td>
</tr>
<tr>
<td>Iluma standard</td>
<td>50</td>
<td>98</td>
<td>97%</td>
</tr>
<tr>
<td>Iluma ultra</td>
<td>252</td>
<td>498</td>
<td>97%</td>
</tr>
<tr>
<td>Average</td>
<td></td>
<td></td>
<td>61%</td>
</tr>
<tr>
<td><strong>Medium FOV</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CB Mercuray panoramic FOV$^d$</td>
<td>264</td>
<td>560</td>
<td>112%</td>
</tr>
<tr>
<td>Classic i-CAT standard scan</td>
<td>29</td>
<td>69</td>
<td>137%</td>
</tr>
<tr>
<td>Next Generation i-CAT landscape mode</td>
<td>36</td>
<td>87</td>
<td>139%</td>
</tr>
<tr>
<td>Galileos default exposure</td>
<td>28</td>
<td>70</td>
<td>148%</td>
</tr>
<tr>
<td>Galileos maximum exposure</td>
<td>52</td>
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<td>148%</td>
</tr>
<tr>
<td>Somaton 64 MDCT</td>
<td>453</td>
<td>860</td>
<td>90%</td>
</tr>
<tr>
<td>Somaton 64 MDCT w/ CARE Dose 4D</td>
<td>285</td>
<td>534</td>
<td>87%</td>
</tr>
<tr>
<td>Average</td>
<td></td>
<td></td>
<td>123%</td>
</tr>
<tr>
<td><strong>Small FOV</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CB Mercuray I FOV maxillary$^d$</td>
<td>156</td>
<td>407</td>
<td>161%</td>
</tr>
<tr>
<td>Promax 3D small adult</td>
<td>151</td>
<td>488</td>
<td>224%</td>
</tr>
<tr>
<td>Promax 3D large adult</td>
<td>203</td>
<td>652</td>
<td>222%</td>
</tr>
<tr>
<td>PreXion 3D standard exposure</td>
<td>66</td>
<td>189</td>
<td>187%</td>
</tr>
<tr>
<td>PreXion 3D high resolution</td>
<td>154</td>
<td>388</td>
<td>151%</td>
</tr>
<tr>
<td>Average</td>
<td></td>
<td></td>
<td>189%</td>
</tr>
</tbody>
</table>

ICRP, International Commission on Radiological Protection.

$^d$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 i-CAT 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 CTDIvoul

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

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

Abbreviations as in Tables I and IV.

\*6.5 \( \mu \)Sv.

†24.5 \( \mu \)Sv, Planmeca Promax digital panoramic device.

\(^4\)Previously published data.
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<sub>vol</sub> 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. Other studies have assessed dose reduction and image quality for reduced-exposure head or sinus 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. 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


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