Dosimetry of a Next Generation i-CAT CBCT machine as compared to a digital panoramic and lateral cephalogram in patient diagnosis and treatment at the University of Minnesota Division of Orthodontics

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Dedication

This thesis is dedicated to my soon-to-be-born first child, who was with me through it all.

Abstract

Background: Three-dimensional cone-beam computed tomography (CBCT) has rapidly gained prominence and exposure in the dental community over the last few years, and is quickly becoming the routine imaging modality for many orthodontic clinics. However, questions remain about the amount of radiation patients are exposed to during the multiple scans needed for the associated advanced diagnostic and treatment techniques.

Objective: To determine the amount of radiation potentially absorbed by a patient during routine orthodontic imaging with the Next Generation i-CAT® cone-beam computed tomography machine with various scan settings. Also, to evaluate the amount of radiation patients at the University of Minnesota Division of Orthodontics are exposed to during a routine two-year treatment including cone-beam scans for diagnosis and for SureSmile® treatment.

Methods: Twenty-four thermoluminescent dosimeters placed at anatomic sites inside a RANDO® phantom were scanned using various scan protocols on a Next Generation i-CAT machine and digital panoramic and cephalometric xray machine. Effective doses were calculated using the 2007 International Commission on Radiological Protection recommended tissue weighting factors.

Results: The effective doses ranged from 108-129μSv for standard resolution CBCT scans at various voxel size and field of view settings; 196-212μSv for enhanced or high-resolution full field of view scans; and measured 252μSv for a high-resolution landscape scan as would be used for SureSmile® therapy. Digital panoramic xray dose was 39μSv and lateral cephalogram was 25μSv.

Discussion: Cone-beam CT, while providing proven diagnostic and therapeutic benefits, also exposes patients to a higher level of radiation than with standard digital 2D examinations. It is important for the clinician to weigh the benefits against the risks when determining their imaging protocol.

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Introduction:

Three-dimensional cone-beam computed tomography (CBCT) has rapidly gained prominence and exposure in the dental community over the last few years, and is quickly becoming the routine imaging modality for many orthodontic clinics. The technology of CBCT has improved since its inception over 20 years ago, allowing for more affordable and mobile machines to become commercially available. This has resulted in a significant enhancement in the amount of radiologic information gained by a clinician, but at the cost of increased ionizing radiation exposure to the patient.

Along with the new technology of capturing an image of a patient in all three dimensions, comes the advent of new software and techniques using this data. Digital impressions have been implemented by some clinicians, reducing or even eliminating the need for alginate impressions and plaster diagnostic models. Multiple companies have introduced programs and software designed to allow dental professionals to manipulate the 3D image data and produce convincingly accurate predictions of surgical or non-surgical treatment outcomes.

However, concerns over the amount of radiation patients are exposed to during the multiple scans needed for these advanced diagnostic and treatment techniques is a current topic of discussion in orthodontic and dental radiology publications. Stochastic effects of radiation, including carcinogenesis and genetic mutations, are of great concern. This type of radiation effect has no minimum threshold for radiation damage, but the probability of an effect is proportional to the radiation dose.[2] Stochastic effects can thus occur with only a single dose of radiation. Cells that are actively mitotic or immature, such as stem cells, are at higher risk of these radiation effects due to possible changes in DNA replication and cell division. This is of special concern to orthodontists as children, the majority of orthodontic patients, are considered especially sensitive to radiation.

It has been reported that a cone-beam scan can expose the patient to anywhere from four to fifteen times the amount of radiation as a standard digital panoramic xray (2.9-11 μSv), or similar to the levels obtained during a full-mouth radiographic survey (13-100 μSv).[3] Before the advent of CBCT, a multi-detector CT (MDCT) was the practitionerôs only option for obtaining a three-dimensional view of a patientôs anatomy. The reduced radiation levels of the CBCT offer a significant benefit when compared to a MDCT scan, but remain significantly higher than the commonly used 2D options for diagnostic radiation exposureð namely, the panoramic and lateral cephalogram.[4,5]

Benefits of cone-beam technology have been reported in the literature as providing a more accurate diagnosis of skeletal asymmetry, easier location of impacted teeth, improved surgical planning, increased detection of pathologies and volumetric evaluation of the airway, among others.[6,7-10] However, some clinicians voice concerns that these benefits are uncertain, and the risk to patients and possible increased liability to clinicians outweighs what advantages there may be to a 3D image.[11]

In 2007, the International Commission on Radiologic Protection (ICRP) released new recommendations regarding absorbed dose calculation.[12] These recommendations were used to determine the appropriate tissue-weighting factor (ω_T) for each anatomic site in radiation exposure calculations. The tissue-weighting factor is derived from epidemiologic data based on those populations exposed to increased levels of radiation, such as the survivors of the World War II atomic bombings in Hiroshima and Nagasaki, Japan, or those who underwent now-obsolete radiation therapy for certain medical conditions at a young age.[2] The ω_T was updated by the ICRP using the most recent scientific information on the nature of radiation exposure. For the first time, salivary glands, extrathoracic airway tissue, and oral mucosa were included. Brain tissueȇs weight was increased, while thyroid and esophageal tissue was given slightly less weight than in previous recommendations (decreased from a 0.05 to a 0.04 weighting factor).[12] This was done due to newly available data on the incidence of cancer as well as the mortality. Previous guidelines have been based on mortality data alone, which gives an incomplete picture of the actual risk to an exposed patient, as some cancers have very high survival rates.

Recent studies calculating effective dose during head and neck exposures using the 2007 guidelines have shown the changes to be significant. Roberts et al. found that the absorbed dose calculated using the 2007 factors is approximately double that found using the 1991 factors.[13] Ludlow found the risk associated with dental radiography to be 32 to 422 percent higher than in 1990 after application of the 2007 guidelines.[12] The majority of the increase can be attributed to the inclusion of the salivary glands, as most dental exposures directly include these tissues in the primary beam.

Multiple studies have examined the dosimetry of various machines, including those types of CBCT machines available to clinical orthodontists. A variety of factors can affect the absorbed dose reported, including machine imaging parameters of kilovolts (kV) and milliamperes (mA), size of the field of view (FOV) for the scanned image, the system of dose reporting, and the dosimetry technique used by the authors of the study. It is important to examine the methods of each study when comparing effective doses among the published results.

Ludlow has published a number of articles regarding the dosimetry of multiple commercially-available CBCT machines.[14-17] In 2003, he found the NewTom 9000Ê CBCT unit to have an effective dose, *E*, of 77.9 μSv for a combined maxillary and mandibular scan. This compared to *E* = 22.0 μSv for a panoramic examination on the Orthophos Plus DS unit.[15] These results were calculated prior to the ICRP 2007 recommendations publication, and are a combination of the 1991 guidelines and a separate salivary gland summation performed by the author.

In 2006, Ludlow et al. compared the effective dose of three full field-of-view CBCT machines: CB Mercuray, NewTom 3G and Classic i-CAT.[16] Using the 2005 draft of the newest ICRP guidelines, the authors found the range of effective doses to be 59-588 μSv for 12ò field size, depending on the machine. The i-CAT machine was in the middle of the range with an effective dose of 193 μSv. These dosages are 4 to 42 times higher than the comparable panoramic examination dose of 13.3 μSv used in this study. It was also found that dose reduction could be obtained with a reduced field size and mA and kV technique parameters. The authors concluded that CBCT dose varies substantially depending on the device, field of view and selected technique factors.

Roberts, et al., replicated this study using similar methodology on an i-CAT machine.[13] This studyôs conclusions found the effective dose of a full FOV scan (0.4mm voxel size) to be 206.2 μSv using the 2007 ICRP guidelines. Compared to a panoramic examination dose of 13 μSv, the authors concluded that the i-CAT CBCT dose was higher by a factor of five to sixteen, with smaller field of view settings resulting in lower doses of radiation.

A study published in 2008 by Palomo, et al., attempted to use the newest ICRP recommendations, but had only the 2005 draft of the 2007 publication available at the time of the study.[18] Their study aimed to show differences in effective dose from a CB MercuRayÊ at various scan settings. Results showed that by using lower kVp settings and reducing the field of view, a smaller effective dose will be absorbed by the patient. While the conclusions are interesting, the data must be read with the knowledge that both calvarium and remainder tissue dosimeter readings were not included, which results in a significant underestimation of the effective dose by a reported factor of 67-141%.[19]

The 2007 guidelines were able to be used in an article published in July, 2008, by Ludlow and Ivanovic.[17] The authors examined the dosimetry for 8 CBCT units and a 64-slice multi-detector CT unit. In relation to the current study, the Next Generation i-CAT machine was evaluated. This is the only available comparative dosimetry data on this particular machine found in the current literature. The authors determined the effective dose of a full FOV scan (0.4mm voxel, 17 cm scan height, 8.9 second scan time, 120 kV and 5mA) to be 74 μSv, and the landscape mode scan (0.25-0.4mm voxel, 13 cm scan height, 8.9 second scan time, 120 kV and 5 mA) to have an effective dose of 87 μSv. These doses are 3-4 times higher than the comparable Planmeca Promax digital panoramic examination effective dose of 24.5 μSv used in this study. Other machinesô effective doses ranged from 3 to 44 times the panoramic dose, across all possible field of view dimensions.

The University of Minnesota Division of Orthodontics in Minneapolis has routinely scanned nearly all new patients using a Next Generation i-CAT® (Imaging Sciences International, Hatfield, PA) CBCT machine since July 2008. These scans are used to generate panoramic images and both frontal lateral cephalograms, as well as detailed images of the temporomandibular joints, impacted canines, and other areas of interest. Recently, the clinic has also incorporated SureSmile® (Orametrix, Richardson, TX) technology into its treatment armamentarium.

SureSmile® is a digital orthodontic system that utilizes CAD/CAM technology to produce custom archwires. Through advanced software, clinicians use a three-dimensional model of a patientôs mouth to manipulate teeth and jaws to simulate orthodontic treatment.[20] A robot then transcribes this virtual treatment by placing the series of bends on an archwire needed to move the patientôs teeth into the prescribed position. This technology allows for more accurate archwire bends and a reportedly 34% faster treatment time.[21] The first step in this process is data acquisition to digitize the patientôs dentition. To this end, in May 2007, SureSmile® began incorporating the use of 3D CBCT scans into its software, allowing clinicians to see anatomy and root positions beneath the tissues. While the University clinic has access to an OraScanner® (intraoral 3D camera), CBCT scans are the preferred method of obtaining a model for the SureSmile® treatment, with the scanner used as needed to supplement the cone-beam if a patient has multiple restorations or other areas unable to be clearly delineated with the 3D imaging. The OraScanner® is a hand-held device used by a trained assistant, who first coats the patientôs teeth in an opacifying liquid. The scanner then takes a series of consecutive digital pictures as the technician slowly passes over and around each individual tooth, creating a 3D model in real time. The time needed to perform the scan can be up to 20-40 minutes, especially for a novice assistant. Benefits of using the CBCT scan over the OraScanner® include not only reduced clinic time, but also increased patient comfort and the ability for the clinician to visualize the roots and surrounding anatomy of each tooth during digital model manipulation.

The purpose of the present study was to determine the amount of radiation potentially absorbed by a patient during routine orthodontic imaging with the Next Generation i-CAT® cone-beam computed tomography machine during various scan settings. Also, the goal was to evaluate the amount of radiation patients at the University of Minnesota Division of Orthodontics are exposed to during a routine two-year treatment including cone-beam scans for diagnosis and SureSmile® treatment, and compare this to the radiation they would receive using traditional 2D digital imaging. It is hoped that through the examination and analysis of this data, clinicians will be able to determine whether the benefit of more information acquired and potentially faster treatment times is worth the increased risk due to higher radiation exposure to patients.

Materials and Methods:

Absorbed dose measurements were collected on two different radiographic units in the University of Minnesota orthodontic and dental clinic: the Next Generation i-CAT® (Imaging Sciences International, Hatfield, PA) cone-beam computed tomography (CBCT) machine and the Orthopantomograph® OP100/OC100 (Instrumentarium Dental, Tuusula, Finland). Thermoluminescent dosimeter (TLD) chips placed at various locations within sections of an adult male RANDO® phantom (The Phantom Laboratory, Salem, NY) head and neck were used to record the radiation exposure delivered by each machine during various scan settings. Scans were representative of those used during diagnosis and treatment of patients at the University of Minnesota Division of Orthodontics.

RANDO® (radiation analog dosimetry) phantoms are constructed using a natural human skeleton that has been cast within a tissue-equivalent gel body form[12] (Figure 1). This soft-tissue model is manufactured from a urethane formula with an effective atomic number and mass density that closely replicates muscle tissue with randomly distributed fat. The phantom is sectioned into 2.5cm axial slices. Hole grids are drilled through the phantomôs individual sections to allow placement of dosimeters within the soft-tissue mold in anatomically representative positions. An example of a phantom slice with grid is shown in Figure 2. In this study, sections 0-9 of the phantom were used, representing the area from the apex of the cranium to approximately the level of the clavicles. Locations of the dosimeters were selected based on the methods of Ludlow,[16,17] and reflect critical organs known to be the most radiosensitive in the head and neck region, along with other sites relevant to dental imaging. This particular study was selected for its strong methodology and because it is one of the most often cited articles in the clinical literature on radiation dose of CBCT in the maxillofacial region.

Figure 1: RANDO® Phantom head, sections 0-9

Figures 2 and 3: Example of phantom axial slices with grid holes for TLD placement

Table 1. Technical factors for CBCT and digital panoramic/cephalometric imaging of maxillofacial areas

Scan Number	*Unit*	*Orientation*	*Filter*	*FOV (cm) **	*Voxel size (mm)*	*Scan time (s)*	*Tube Energy (kV)*	*Tube current (mAs)*
1	Next Generation i-CAT	Portrait	Standard	17cm	0.3	8.9	120	18.54
2	Next Generation i-CAT	Portrait	Standard	17cm	0.3 enhanced	17.8	120	37.10
3	Next Generation i-CAT	Portrait	Standard	17cm	0.4	8.9	120	8.90
4	Next Generation i-CAT	Portrait	Standard	17cm	0.4 enhanced	17.8	120	37.10
6	Next Generation i-CAT	Landscape	Standard	8cm	0.3	8.9	120	18.54
7	Next Generation i-CAT	Landscape	SureSmile	8cm	0.2	26.9	120	37.07
8	Orthopantomograph OP100	Panoramic	N/A			17.6	73	12.00
9	Orthopantomograph OC100	Lateral Ceph	N/A			16	85	12.00

* FOV (Field of View)

All dose measurements in this study were gathered using TLD-100 lithium fluoride chips, calibrated for use in the appropriate radiologic conditions (Table 1). Each dosimeter is 3mm x 3mm x 1mm, and comes packaged in an individual plastic sleeve to protect it from humidity and contamination. All chips were provided, calibrated and analyzed by Landauer, Inc. (Glenwood, IL). Each set of TLDs was accompanied by a transit control to account for potential environmental radiation exposure during shipping.

Table 2. Locations of TLD chips in RANDO phantom

Phantom location (level/slice)	*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.
*Indicates placement on surface of phantom

TLDs were placed at 24 sites within the phantom to record the distribution of the absorbed dose, as listed in Table 2. Before the dosimeters were placed for the cone-beam imaging scans, a scout image was taken to ensure correct positioning of the phantom. Thus, dosage calculations for these scans do not include these scout images, which are the equivalent of 1/360 of the dose (one ñsliceò). All dosimeters were placed by the same operator to ensure consistency of location and position, and unoccupied drill-holes within the phantom were filled with tissue-equivalent rods. TLDs intended to record dosages to surface landmarks were held in place with clear tape. After placement of the dosimeters, the phantom was positioned in each machine with the midsagittal plane centered in the image field and the occlusal plane as parallel to the floor as possible while ensuring the entire region of interest was within the field of view. The soft tissue profile was captured on all full field of view scans (Figure 4). To avoid possible scatter, the phantom was placed on a platform of non-metallic items (cardboard boxes and plastic bases) to achieve the ideal vertical position (Figure 5). An additional control dosimeter was kept near the operator during each scan to allow the later establishment and subtraction of any accumulated background radiation dose.

Figure 4: Computer screen image of the full field-of-view CBCT scan

Figure 5: Set up of phantom in proper scanning position within the NextGeneration iCAT CBCT machine

Doses for the two machines were investigated using nine separate scans (six CBCT protocols with one duplicated scan, a lateral cephalogram and a panoramic xray) performed at various settings. Each scan was repeated three times without changing the position of the phantom to ensure the minimum threshold dose of 10mGy for each dosimeter was met. Later, dosages were divided by three to determine the exposure per scan for each chip. All routinely used settings of each machine were used for the CBCT scans. The parameters of kV and mAs for each scan were fixed at the machinesô manufacturer-recommended settings for an average adult male patient, and are the settings routinely used in the University clinic (Table 1).

Table 3. Estimated percentage of tissue irradiated and TLDs used to calculate mean absorbed dose to a tissue or organ.

	Fraction irradiated	*TLD ID (See Table 2)*
Bone marrow	16.5%	
Mandible	1.3%	13, 14, 17, 18
Calvarium	11.8%	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		
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 x bone/muscle mass energy absorption coefficient ratio (MEACR). MEACR = -0.0618 x 2/3 kV peak + 6.9406 using data taken from Nation Bureau of Standards handbook no. 85.

Absorbed dose data was received from Landauer, Inc., with all dosages recorded in units of millirads (mrad). These measures were then converted to the International System (SI) unit of micrograys (μGy), where 1 mrad = 10 μGy. Calculations were performed to determine the *radiation weighted dose* in microsieverts (H_T) (also known as *equivalent dose*), given by the product of the background-subtracted mean organ TLD dose and the fraction of that tissue or organ in the irradiated field (Table 3).

$$H_T \ (\mu Sv) = \text{absorbed dose } (\mu Gy) \text{ x fraction irradiated}$$

The percentage used as the multiplier for fraction of tissue irradiated was determined following Ludlowȏs published estimates for full field of view scans.[16] Other studies have used different estimates for smaller scan sizes,[13] but no protocol could be found for the 8cm landscape CBCT scan used in this study. It was decided to use the full field of view percentages to avoid any underestimation of resulting dosages.

Equivalent dose for bone marrow was calculated using the sum of the individual equivalent doses to the calvarium, the mandible, and the cervical spine. These equivalent doses were based on Whiteȏs published distributions of bone marrow in an adult body (11.8%, 1.3% and 3.4%, respectively).[22]

As performed by Underhill et al., and replicated in current accepted dosimetry studies, three TLD sites in the calvarium were averaged to determine the total calvarial dose.[23] In the style of Ludlow, bone surface dose was calculated to be the product of the bone marrow dose for each TLD site and the bone/muscle mass energy absorption coefficient ratio (MEACR) where MEACR = -0.0618 x 2/3 kV peak + 6.9406 using data from the National Bureau of Standards handbook number 85.[17]

Table 4. Tissue-weighting factors for calculation of effective dose—ICRP 2007 recommendations.

Tissue	*2007 w_T*
Breast	0.12
Colon	0.12
Lung	0.12
Stomach	0.12
Bladder	0.04
Esophagus	0.04
Gonads	0.08
Liver	0.04
Thyroid	0.04
Bone Surface	0.01
Brain	0.01
Salivary Glands	0.01
Skin	0.01
Remainder Tissues*	0.12

ICRP, International Commision on Radiological Protection

*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.

The *effective dose (E)*, in microsieverts, was then calculated as the sum of all tissuesô radiation weighted dose multiplied by its corresponding 2007 ICRP tissue-weighting factor (ω_T) (Table 4):

$$E = \sum \omega_T \text{ x } H_T$$

Effective dose represents the absorbed dose relative to the whole body, and gives a general indication of the level of risk to an exposed patient. It takes into account different organsô sensitivities to long-term radiation exposure, and is the preferred method for comparing absorbed doses from different exposure techniques.[2]

To test reproducibility of the imaging methods employed, the 0.3 voxel portrait CBCT scan was performed at two separate times. This allowed for evaluation of technique error, such as variations in phantom or TLD positioning, through differences in the calculated effective dose from the gathered data.

Results:

The reproducibility of two different i-CAT scans was calculated using repeated 0.3mm voxel, full FOV exams at settings of 120kV and 18.54mAs. Dosimeter values (mrad) for the two scans are reported in Table 5. A high level of reproducibility is seen by an overall percent variation between the two scans of less than 1%.

Table 5: Dosimetry reproducibility: Next Generation i-CAT CBCT Full field of view – 0.3mm voxel, 120kV, 18.54mAs

Phantom location	*TLD ID*	*Scan 1 (mRad)*	*Scan 2 (mRad)*	*Percent variation 1 from 2*
Calvarium anterior (2)	1	106.67	100.00	6%
Calvarium left (2)	2	76.67	73.33	4%
Calvarium posterior (2)	3	66.67	70.00	-5%
Midbrain (2)	4	80.00	83.33	-4%
Pituitary (3)	5	100.00	100.00	0%
Right orbit (4)	6	83.33	80.00	4%
Left orbit (4)	7	100.00	96.67	3%
Right lens of eye* (3)	8	93.33	93.33	0%
Left lens of eye* (3)	9	93.33	86.67	7%
Right cheek* (5)	10	103.33	90.00	14%
Right parotid (6)	11	130.00	116.67	11%
Left parotid (6)	12	113.33	136.67	-19%
Right ramus (6)	13	106.67	96.67	10%
Left ramus (6)	14	116.67	113.33	3%
Center cervical spine (6)	15	93.33	93.33	0%
Left back of neck* (7)	16	26.67	30.00	-12%
Right mandible body (7)	17	110.00	106.67	3%
Left mandible body (7)	18	100.00	96.67	3%
Right submandibular gland (7)	19	116.67	133.33	-13%
Left submandibular gland (7)	20	130.00	123.33	5%
Center sublingual gland (7)	21	106.67	116.67	-9%
Midline thyroid (9)	22	23.33	20.00	15%
Thyroid surface--left* (9)	23	10.00	13.33	-29%
Esophagus (9)	24	16.67	16.67	0%
Average TLD Dose		87.64	86.94	1%

Equivalent doses for the weighted tissues which were directly exposed during each of the eight scans are reported in Table 6. Some dosimeters used in the phantom during the digital radiographs on the Orthopantomograph® OP100 were not exposed at levels above the minimum chip exposure threshold of 10mrads (100μGys) despite being exposed for three consecutive scans. In those cases, the maximum possible unrecordable dose of 9mrads over three scans (3mrads per scan) was used in the calculations to avoid any underestimation of the effective dose. Even when these dosimeters were entirely left out of the calculations, the effect on the total equivalent dose was negligible. In the panoramic scan, no change was seen in the equivalent does; in the cephalometric scan, a variation of 2μSv (25 μSv to 27 μSv) was seen depending on whether those dosimeters were included.

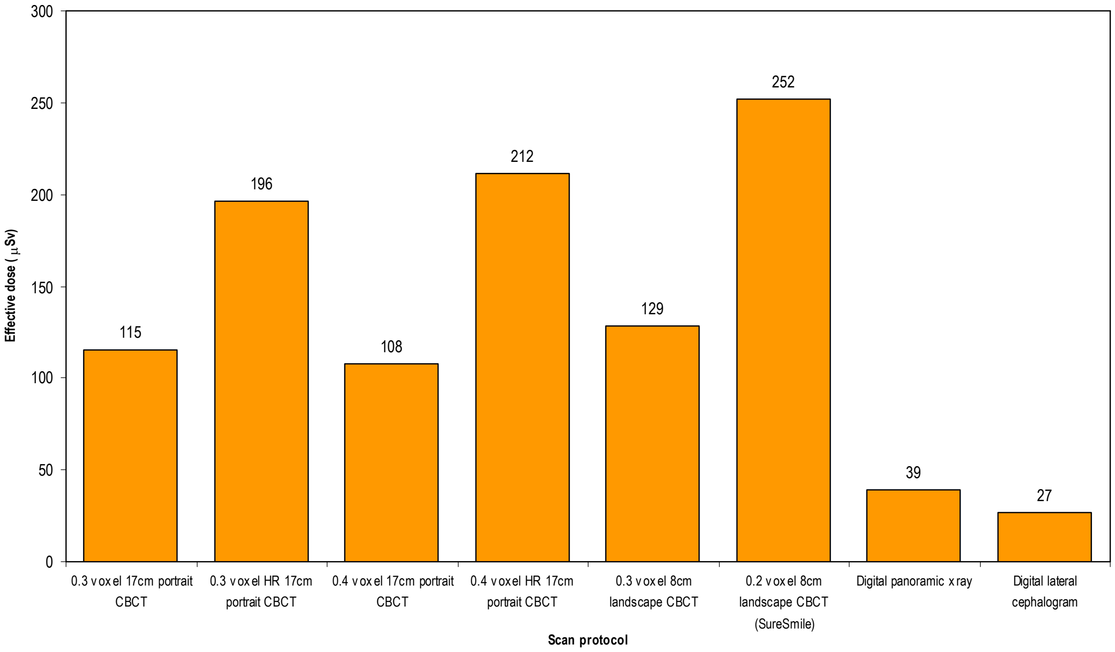
Table 6. Equivalent dose (μSv) to tissues/organs in the head and neck from various scan techniques, digital and CBCT

									Remainder tissues/organs			
Scan #	*Scan Protocol*	*Bone Marrow*	*Thyroid*	*Esophagus*	*Skin*	*Bone Surface*	*Salivary Glands*	*Brain*	*Lymphatic Nodes*	*Extrathoracic region*	*Muscle*	*Oral Mucosa*
1‡	0.3 voxel 17 cm portrait CBCT, 8.9s	143	167	17	39	285	1223	908	49	962	49	1150
2	0.3 voxel HR 17cm portrait CBCT, 17.8s	250	267	30	84	499	2307	1667	80	1607	80	1856
3	0.4 voxel 17cm portrait CBCT, 8.9s	134	150	13	38	268	1127	867	46	907	46	1081
4	0.4 voxel HR 17cm portrait CBCT, 17.8s	213	350	37	77	424	2287	1700	92	1824	92	2181
5	0.3 voxel 8cm landscape CBCT, 8.9s	76	183	17	33	151	1647	150	70	1240	70	1674
6	0.2 voxel 8cm landscape CBCT (SureSmile), 26.9s	144	367	313	65	287	3180	317	136	2414	136	2952
7	Digital panoramic xray*	22	67	7	7	44	647	30	21	359	21	481
8	Digital lateral cephalogram*	8	30	3	2	15	973	32	23	397	23	59
**	0.4 voxel 17cm portrait CBCT, 8.9s, 19mAs	147	183	33	52	294	1250	950	54	1083	54	1226

‡ Average of two dosimeter runs
*Some values estimated due to incomplete chip exposure
**Per Ludlow, 2008[17]

Salivary gland tissue shows the greatest equivalent dose across all imaging protocol variations except scan #5, 0.3mm voxel landscape CBCT, where oral mucosa was slightly greater. In all other scans except the digital lateral cephalogram, oral mucosa demonstrated the second-highest equivalent dose. Thyroid doses ranged from approximately 150-350μSv depending on scan settings. Equivalent doses of a comparable Next Generation i-CAT® scan from Ludlowŝs published results are also given for comparison.[17]

Figure 6. Effective dose (μSv) for all scan protocols



Calculated effective doses for all scan protocols are shown in Figure 6. The percent range of variation in effective dose between the repeated scans was 0.56%. The full field of view (17cm portrait) cone-beam imaging effective dosage ranged from 108-115μSv, depending on voxel size. High resolution or enhanced scans, whose major setting variation is a doubled scan time, had effective doses that increased to approximately 200μSv per scan. The 8cm FOV image effective dose was 129μSv, and the SureSmile® scan demonstrated the highest effective dose at 252μSv.

Effective doses for the 2D digital radiography in this study are estimated due to some chips being exposed to doses too low to be recorded. The highest possible effective dose is 39μSv for the panoramic xray and 27μSv for the lateral cephalogram.

Table 7. Next Generation i-CAT effective dose as a result of varying imaging parameters and as a percentage of the average natural background dose received in the US each year, and in terms of radiation detriment

Imaging parameters	*Effective Dose (μSv)*	*Dose as a multiple of digital panoramic xray*	*Dose as % of annual background dose in US*	*Probability of fatal cancer out of 1 million**
0.3 voxel 17cm portrait CBCT	115	2.96	3.84%	6.34
0.3 voxel HR 17cm portrait CBCT	196	5.03	6.54%	10.78
0.4 voxel 17cm portrait CBCT	108	2.77	3.60%	5.94
0.4 voxel HR 17cm portrait CBCT	212	5.42	7.05%	11.63
0.3 voxel 8cm landscape CBCT	129	3.30	4.28%	7.07
0.2 voxel 8cm landscape CBCT (SureSmile)	252	6.46	8.40%	13.86
Digital panoramic xray	39	1.00	1.30%	2.15
Digital cephalometric xray (minimum dose)	25	0.64	0.83%	1.38
Digital cephalometric xray (maximum dose)	27	0.69	0.90%	1.49

* From Ludlow, 2007

Table 7 demonstrates the relation of all this studyǿs scan parameters to the Orthopantomograph® OP100 digital panoramic xray, and as a percentage of the average annual background dose of 3000μSv in the United States.[24] Also included is the risk of fatal cancer occurring out of one million people, calculated using Ludlowǿs risk coefficient of 5.5 X 10^{-2} Sv^{-1} (2007 ICRP guidelines).[17]

Discussion:

The routine use of cone-beam imaging in orthodontic treatment is an area of intense discussion among dental practitioners. The balance between information gained or improvement in patient care with the use of CBCT imaging and the exposure of a patient to higher levels of radiation must be evaluated.

The present study sought to evaluate the amount of radiation a patient is exposed to during various scans with the Next Generation i-CAT® cone-beam CT and Orthopantomograph OP100® digital xray machine. This information can then be used to evaluate the risk/benefit ratio of routine three-dimensional scans in orthodontic diagnosis and treatment.

In Table 6, equivalent doses in μSv for all scan protocols are given. In all settings except one, salivary gland tissue received the highest amount of radiation exposure. This is in agreement with Chau and Fung in 2009, who showed that doses of radiation received by the salivary glands were 14-24 times more than the thyroid, depending on the location of the scanʼs field of view (maxillary or mandibular).[25] Other studies who examined the exposure from CBCT to individual organs found a similar pattern.[5,17] Salivary gland tissue tends to be in the center of the imaging field, and receives near-constant exposure during the rotation of the sensor and beam. This is a major reason for the increased effective dosage seen when using the newest ICRP guidelines, as salivary gland tissue had never been included in the calculations before. Studies comparing the 2007 guidelines to the previously used 1991 guidelines have found that the dose to salivary glands is approximately doubled.[13]

The inclusion of the thyroid gland is also important for the clinician to understand. This area was given the highest tissue-weighting factor in the head and neck region, because this organ has a high risk of childhood cancer.[16] Consideration of the exposure of this organ should always be taken into account by a responsible practitioner.

Effective dose calculation was performed by the author, and reviewed by a board-certified radiation physicist (Dr. E. Russel Ritenour) for accuracy. As limited data is available for this particular machine (Next Generation i-CAT), it is difficult to show consistency with other studies. However, Ludlow and Ivanovich found an effective dose of 74µSv using a scan protocol similar to the current scan #3 (Table 1).[17] The current study found the same protocol to yield an effective dose of 108µSv. The individual organsô equivalent doses given in their results are in good correlation with those found in this study, and it can be assumed that other scan protocols would have agreed as well. The variation seen in effective dose can be attributed to individual machine or phantom differences.

A similar pattern is seen with the higher effective dose calculated for the digital panoramic and cephalometric xrays. No studies have been performed using the same phantom technique with the Orthopantomograph OP100 machine. Ludlow, et al., evaluated a ProMax (Planmeca) machine operated at 68kV and 13mA with a 16 second exposure time, and found an effective dose of 24.3µSv using the ICRP 2007 tissue weights.[12] This study found a maximum possible effective dose of 39mSv, accounting for the few TLDs that were unreadable. Again, error in the dosimeters, variation in machine settings and phantom composition can account for these differences.

Table 8. Major benefits and limitations of CBCT imaging in the oral and maxillofacial region, condensed from DeVos 2009[1]

- Benefits:
  - 3D dataset
  - Real-size data
  - Potential for generating all 2D images
  - Isotropic voxel size
  - High resolution
  - Lower dose than multi-slice CT (MSCT)
  - Easy accessibility
  - In-office imaging
  - DICOM compatible
  - User-friendly processing and software
- Limitations:
  - Low contrast range
  - Limited detector size (limted FOV and scanned volume)
  - Limited inner soft tissue information
  - Increased noise and concomitant loss of contrast resolution
  - Movement artefacts

Recent publications debate the merit of 3D imaging over 2D imaging in standard orthodontic care.[26,27] The benefits of a cone-beam CT have been touted in the literature since the late 1990ôs, when scanners dedicated to the oral and maxillofacial region were introduced.[1] A systematic review of the literature from 1998 through 2007 was performed by DeVos, et al.,[1] and revealed a long list of both benefits and limitations of oromaxillofacial imaging using CBCT (Table 8). These refer primarily to the technological advantages, and not to the multiple diagnostic and therapeutic benefits discussed previously.

Most practitioners believe CBCT should be used with caution, and only in certain situations. In the April 2010 issue of the *American Journal of Orthodontics and Dentofacial Orthopedics*, Dr. Vince Kokich questions the ability of 3D imaging to provide any benefit other than simply providing more informationð perhaps more information than needed.[11] He challenges practitioners to make their decisions based on whether the benefit outweighs the potential risk to the patient.

This sentiment is repeated throughout the literature. Farman and Scarfe suggested capturing very low dose lateral cephalograms using the CBCT by taking only one slice in the traditional cephalometric view, and then evaluating that single image for a potential need of further 3D examination.[28] The volumetric exam could be done using specific collimation of the beam, thus minimizing the absorbed dose the patient would receive. The authors urge in their conclusions that the ALARA (As Low As Reasonably Achievable) principal , promoted in all aspects of dental radiology, be used to develop evidence-based selection criteria for CBCT use in orthodontics. In 2009, White and Pae did just that, through their proposal of an algorithim for obtaining radiographic images of patients undergoing orthodontic care.[29] Their selection criteria suggest that a cone-beam examination should be performed only on those patients with severe facial asymmetry or disharmony, sleep apnea, impacted maxillary canines, or for evaluation of bone when mini-implants are being considered. In almost all other cases, excluding symptomatic temporomandibular joint or surgical patients, only a lateral cephalometric and panoramic view is recommended for diagnosis.

The risk can be more easily imagined when put into terms of odds of inducing cancer or even death. Based on the ICRP probability coefficient of 6.0×10^{-2} Sv^{-1}, the risk of causing cancer or another stochastic effect through the use of a CBCT machine has been calculated by Brooks to be 3.5 to 61.5×10^{-6} for a full field-of-view cone beam examination.[2] It is unknown whether this risk is significant enough to be concerned with, as there is no good statistical model to calculate the actual risk of such low doses. Risks such as these are calculated using the linear non-threshold estimate model,[2,12,27] which takes the mathematically calculable higher-dosage risks and extrapolates them to the very low levels used in dental radiography, assuming no threshold dose needs to be reached before risk is incurred. If there is in fact a threshold, however, then the risk to patients could very well be zero. Ludlow has measured radiation detriment, or the harm that can be done to an exposed population and its descendents, using a risk coefficient of 0.055 fatal cancer events per Sv.[12] Using this coefficient, he found the probability of fatal cancer occurring from a digital panoramic xray to be 1.3 in a million.

In Table 7, the current data is shown in terms of percentage of annual background dose in the US, probability of X in a million fatal cancer, and dose as a multiple of the digital panoramic xray effective dose of 39μSv. The highest risk comes from the scan protocol used for SureSmile therapy (Table 1, #7), with a probability of 13.86 in a million risk of fatal cancer. This is 8.4% the annual background dose, or the equivalent of 30.6 days (one month) of radiation exposure. The lowest CBCT scan effective dose was found to be protocol #3, a 0.4 voxel portrait setting. This scan carries a risk of fatal cancer in the area of 5.94 in a million, and 3.6% of the annual background dose (approximately two weeks of average daily exposure). In contrast, a lateral cephalogram, even with the maximum possible dose of 25μSv, is the equivalent of 3 days exposure.

A typical treatment at the University of Minnesota orthodontic clinic, including SureSmile® therapy, would include an initial diagnostic cone-beam CT scan at the settings of scan #1 (0.3mm voxel, 17cm portrait), a SureSmile® scan, and a final CBCT image at the same initial settings. The total effective dose to the patient in this scenario is calculated to be 482µSv over a period of approximately 18 months to 2 years, assuming no retakes of the imaging are required.

Without SureSmile® treatment, a patient will receive the same two CBCT images at the beginning and end of treatment, with a progress digital panoramic xray at approximately 12 months into full treatment to evaluate root parallelism, root resorption and presence of any pathology. Effective dose in this scenario is 269µSv, or just greater than the total effective dose for a single SureSmile® scan.

Prior to the incorporation of 3D imaging, a patient would receive a minimum effective dose of 128µSvð initial and final digital panoramic and lateral cephalometric images, with a progress panoramic examination again at the halfway point. Some additional imaging may be requested in the case of impacted canines or orthognathic surgery, for example, adding to the total dose.

It is difficult to find fault with the search for knowledge and the accumulation of available data by reasonable means. However, it is the responsibility and professional obligation of a conscientious practitioner to weigh the proven and perceived benefits of diagnosis and therapy, as well as the usefulness of the data collected for future research, against the risks to which the patient is exposed. At a minimum, the patient must be educated about the risks and benefits of the procedures, and allowed to make an informed decision as to their treatment preference.

References:

1. De Vos W, Casselman J, Swennen GR. Cone-beam computerized tomography (CBCT) imaging of the oral and maxillofacial region: a systematic review of the literature. *Int J Oral Maxillofac Surg*. 2009;38(6):609-625.

2. Brooks SL. CBCT Dosimetry: Orthodontic Considerations. *Semin Orthod*. 2009;15(1):14-18.

3. Scarfe WC, Farman AG, Sukovic P. Clinical applications of cone-beam computed tomography in dental practice. *J Can Dent Assoc*. 2006;72(1):75-80.

4. Loubele M, Bogaerts R, Van Dijck E, et al. Comparison between effective radiation dose of CBCT and MSCT scanners for dentomaxillofacial applications. *Eur J Radiol*. 2009;71(3):461-468.

5. 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(3):413-417.

6. Haney E, Gansky SA, Lee JS, et al. Comparative analysis of traditional radiographs and cone-beam computed tomography volumetric images in the diagnosis and treatment planning of maxillary impacted canines. *Am J Orthod Dentofacial Orthop*. 2010;137(5):590-597.

7. Treister NS, Friedland B, Woo S. Use of cone-beam computerized tomography for evaluation of bisphosphonate-associated osteonecrosis of the jaws. *Oral Surgery, Oral Medicine, Oral Pathology, Oral Radiology, and Endodontology*. 2010;109(5):753-764.

8. Silva MA, Wolf U, Heinicke F, Bumann A, Visser H, Hirsch E. Cone-beam computed tomography for routine orthodontic treatment planning: a radiation dose evaluation. *Am J Orthod Dentofacial Orthop*. 2008;133(5):640.e1-640.e5.

9. Angelopoulos C, Thomas S, Hechler S, Parissis N, Hlavacek M. Comparison Between Digital Panoramic Radiography and Cone-Beam Computed Tomography for the Identification of the Mandibular Canal as Part of Presurgical Dental Implant Assessment. *Journal of Oral and Maxillofacial Surgery*. 2008;66(10):2130-2135.

10. Farman AG, Scarfe WC. The Basics of Maxillofacial Cone Beam Computed Tomography. *Semin Orthod*. 2009;15(1):2-13.

11. Kokich VG. Cone-beam computed tomography: Have we identified the orthodontic benefits? *American Journal of Orthodontics and Dentofacial Orthopedics*. 2010;137(4, Supplement 1):S16-S16.

12. Ludlow JB, Davies-Ludlow LE, White SC. Patient risk related to common dental radiographic examinations: the impact of 2007 International Commission on Radiological Protection recommendations regarding dose calculation. *J Am Dent Assoc*. 2008;139(9):1237-1243.

13. Roberts JA, Drage NA, Davies J, Thomas DW. Effective dose from cone beam CT examinations in dentistry. *Br J Radiol*. 2009;82(973):35-40.

14. Ludlow JB. Dosimetry of the Kodak 9000 3D Small FOV CBCT and Panoramic Unit. *Oral Surgery, Oral Medicine, Oral Pathology, Oral Radiology, and Endodontology*. 2009;107(4):e29-e29.

15. 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(4):229-234.

16. Ludlow JB, Davies-Ludlow LE, Brooks SL, Howerton WB. Dosimetry of 3 CBCT devices for oral and maxillofacial radiology: CB Mercuray, NewTom 3G and i-CAT. *Dentomaxillofac Radiol*. 2006;35(4):219-226.

17. Ludlow JB, Ivanovic M. Comparative dosimetry of dental CBCT devices and 64-slice CT for oral and maxillofacial radiology. *Oral Surg Oral Med Oral Pathol Oral Radiol Endod*. 2008;106(1):106-114.

18. Palomo JM, Rao PS, Hans MG. Influence of CBCT exposure conditions on radiation dose. *Oral Surg Oral Med Oral Pathol Oral Radiol Endod*. 2008;105(6):773-782.

19. Ludlow JB. Regarding "Influence of CBCT exposure conditions on radiation dose". *Oral Surg Oral Med Oral Pathol Oral Radiol Endod*. 2008;106(5):627-8; author reply 628-9.

20. Lin EY, Getto P. SureSmile applies CBCT to custom orthodontic therapy. SureSmile Web site. http://www.suresmile.com/. Updated 2008.

21. OraMetrix Inc. www.suresmile.com, 2010.

22. White SC, Rose TC. Absorbed bone marrow dose in certain dental radiographic techniques. *J Am Dent Assoc*. 1979;98:553-558.

23. Underhill TE, Chilvarquer I, Kimura K, et al. Radiobiologic risk estimation from dental radiology : Part I. Absorbed doses to critical organs. *Oral Surgery, Oral Medicine, Oral Pathology*. 1988;66(1):111-120.

24. Mettler FA,Jr, Huda W, Yoshizumi TT, Mahesh M. Effective doses in radiology and diagnostic nuclear medicine: a catalog. *Radiology*. 2008;248(1):254-263.

25. Chau ACM, Fung K. Comparison of radiation dose for implant imaging using conventional spiral tomography, computed tomography, and cone-beam computed tomography. *Oral Surgery, Oral Medicine, Oral Pathology, Oral Radiology, and Endodontology*. 2009;107(4):559-565.

26. Hatcher D, Hatcher D. Cone beam CT--anatomic assessment and legal issues: the new standards of care. *J Calif Dent Assoc*. 2009;37(9):653-62.

27. Zinman EJ, White SC, Tetradis S. Legal Considerations in the Use of Cone Beam Computer Tomography Imaging. *J Calif Dent Assoc*. 2010;38(1):49-50, 51, 52, 53, 54, 55, 56.

28. Farman AG, Scarfe WC. Development of imaging selection criteria and procedures should precede cephalometric assessment with cone-beam computed tomography. *American Journal of Orthodontics and Dentofacial Orthopedics*. 2006;130(2):257-265.

29. White SC, Pae E. Patient Image Selection Criteria for Cone Beam Computed Tomography Imaging. *Semin Orthod*. 2009;15(1):19-28.