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Effective radiation dose of ProMax 3D cone-beam computerized tomography scanner with different dental protocols

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Objectives. The aim of this study was to compare effective doses resulting from different scan protocols for cone-beam computerized tomography (CBCT) using International Commission on Radiological Protection (ICRP) 1990 and 2007 calculations of dose.

Study design. Average tissue-absorbed dose, equivalent dose, and effective dose for a ProMax 3D CBCT with different dental protocols were calculated using thermoluminescent dosimeter chips in a human equivalent phantom. Effective doses were derived using ICRP 1990 and the superseding 2007 recommendations.

Results. Effective doses (ICRP 2007) for default patient sizes from small to large ranged from 102 to 298 μSv. The coefficient of determination (R^2) between tube current and effective dose (ICRP 2007) was 0.90. When scanning with lower resolution settings, the effective doses were reduced significantly ($P < .05$).

Conclusions. ProMax 3D can provide a wide range of radiation dose levels. Reduction in radiation dose can be achieved when using lower settings of exposure parameters. (**Oral Surg Oral Med Oral Pathol Oral Radiol Endod 2010;110:770-776**)

Cone-beam computerized tomography (CBCT) can provide 3-dimensional (3D) information of the facial skeleton and teeth. Compared with helical computerized tomography (CT), this technology results in images of high quality while using less expensive equipment and components and potentially a lower radiation dose.[1] Therefore, it has been introduced as an alternative imaging technology for diagnostic tasks, including oral surgery,[2] oral medicine,[3,4] endodontics,[5] periodontology,[6] orthodontics,[7] and implantology.[8]

With CBCT technology more widely applied in dental specialties, many new devices have been developed with some advanced technologies.[9] Improvements in CBCT units make it more convenient for dentists to acquire and analyze images and more comfortable for patients to undergo examination.[10] The dose from CBCT is reported to be significantly lower than that from helical CT.[11,12] However, significant differences in dose for the same examination have been reported for different CBCT units, and significant differences in dose have been reported for different examinations or techniques with the same unit.[11] Because x-ray risks are cumulative, it is imperative that strategies for dose reduction, including selection of exposure parameters, be considered in examining all patients.[9] The effect of different dental application protocols on the dose from the same CBCT unit has not been sufficiently studied. If the dose changes appreciably with the selection of different exposure parameters, it is important for the CBCT operator to thoroughly un-

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Table I. Exposure parameters for ProMax 3D imaging of maxillofacial areas

Scan no.	Patient size	Volume height	Volume diameter	Resolution	kV	mA	Exposure time (s)
1	Smallest	Full	Full	Normal	84	8	12
2	Smaller	Full	Full	Normal	84	10	12
3	Middle	Full	Full	Normal	84	12	12
4	Larger	Full	Full	Normal	84	14	12
5	Largest	Full	Full	Normal	84	16	12
6	Largest	Half-upper	Full	Normal	84	16	12
7	Largest	Half-lower	Full	Normal	84	16	12
8	Largest	Full	Half-anterior	Normal	84	16	12
9	Largest	Full	Half-posterior	Normal	84	16	12
10	Largest	Full	Full	Lowdose	84	8	2.8
11	Largest	Full	Full	Highdose	84	16	12
12*	Largest	Full	Full	Lowdose	84	8	8.4

*Three horizontally displaced volumes acquired for stitching into a single volume.

derstand the effects of the scanning parameters and their impact on radiation safety.[13]

Among commercially available CBCT units, the ProMax 3D (Planmeca, Helsinki, Finland) provides a small field of view that is well suited to general dentistry diagnostic procedures involving evaluation of limited dentoalveolar areas. However, the variety of selectable exposure parameters for dentists to choose may be confusing for an operator without advanced radiology training. Because of this and general ignorance about principles and best indications for CBCT use, the opportunity for misuse or abuse of the technology is great. The aim of the present study, therefore, was to determine the effective dose levels of the ProMax 3D unit while varying exposure parameters that may be used for different dental examinations.

MATERIALS AND METHODS

The ProMax 3D CBCT scanner investigated in this study provides 4 selectable imaging parameters which may affect patient dose: patient size, volume size, image resolution, and field of view (FOV). Five default patient sizes adjust milliamperage (mA) in 2-mA increments from smallest (8 mA) to largest (16 mA). Three image volume sizes are available. The largest volume is 80 × 80 mm (height × diameter) and is intended to include the dentate region of both upper and lower jaws. An intermediate scan volume (50 × 80 mm) can be applied in examination of the maxilla or mandible only. The smallest scan volume reduces the volume diameter by one-half (50 × 40 mm) and can be applied in examination of sextants of individual arches. Three selectable resolutions are available: low, normal, and high dose. Furthermore, ProMax 3D software can stitch 2 or 3 views together to cover a larger anatomic area if that is desired. When this function is selected, the resolution is restricted to the "low dose" setting by the manufacturer. The dental protocols were therefore defined by the different combinations of patient size, volume size, and image resolution. For the largest examination area, 3 horizontal full-volume diameter views were acquired at lower resolution for stitching in this study (Table I). The exposure parameters for each of the dental protocols examined in this study are also presented in Table I.

The absorbed doses were measured by using thermoluminescent dosimeter chips (TLDs; LiF:Mg,Cu,P). Before the study, all dosimeters were calibrated using a Co-60 source. Three chips were positioned at each of 21 locations within the head and neck region of an anthropomorphic adult human male phantom (model ART-210; Radiology Support Devices, Long Beach, CA, USA). This phantom is constructed to simulate skeletal and soft tissue anatomic location and attenuation characteristics, and it closely conforms to the International Commission on Radiation Units and Measurements specifications.[14] The method described by Ludlow et al.[11] was used to position the TLD chips (Table II). Before loading, the chips were annealed at 240°C for 10 minutes and then cooled immediately to ambient temperature. All chips were read within 90 minutes after each exposure by using a BR2000D reader (Bochuangte Science and Technology Development Co., Beijing, China). The coefficient of variation (standard deviation of measurements ÷ mean of measurements) was used to determine the consistency of dose measurement by the TLD system. Each of the 3 TLD values for 21 anatomic locations in protocol nos. 1-5 was assessed using 1-way analysis of variance (ANOVA). The average coefficient of variation was 8%. The 8% variation in individual TLDs is consistent with typical tolerances of ±5% that are reported by commercial processors of TLD 100s (LiF: Mg, Ti).[15] There was no statistical association with dosimeter location ($P = .78$) or protocol ($P = .10$).

Table II. Locations of thermoluminescent dosimeter chips (TLDs)

TLD ID	Phantom location	Level
1	Calvarium anterior	2
2	Calvarium right	2
3	Calvarium posterior	2
4	Mid brain	2
5	Pituitary	3
6	Right orbit	4
7	Left orbit	4
8	Right lens of eye	3
9	Left lens of eye	3
10	Left cheek	5
11	Right parotid	6
12	Left parotid	6
13	Right 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	Thyroid	9
21	Esophagus	9

During each examination, 6 nonirradiated TLDs were kept outside the scanning room to measure the background radiation dose, which was subtracted from the measured dose values later on. To ensure that even small radiation doses could be measured, the exposure was repeated 5 times during each examination protocol without changing the phantom position. Measured values from TLDs at different positions within a tissue or organ were divided by 5 to express the average tissue-absorbed dose per examination in micrograys (μGy). Although our measured values represent an average of 5 exposures, it is reasonable to assume that the radiation dose delivered on each exposure is similar for properly operated and well maintained CBCT units.

As suggested by Roberts et al.,[16] the average absorbed dose and the percentage of a tissue or organ irradiated in an examination (Table III) were used to calculate the radiation-weighted dose (H_T) in microsieverts (μSv). For bone surface, a correction factor based on experimentally determined mass energy attenuation coefficients for bone and muscle irradiated with monoenergetic photons was applied following the procedure of Ludlow et al.[11] The effective beam energy for the ProMax 3D was estimated to be two-thirds of the peak energy of 84 kV. With this, a multiplication factor of 3.46 was calculated.

Using both the 1990[17] and 2007[18] International Commission on Radiological Protection (ICRP)–recommended tissue weights (Table IV), the effective dose (μSv) was calculated for the 12 scanning protocols of the ProMax 3D. The effective dose was calculated as the product of the equivalent dose and the relevant ICRP tissue-weighting factor (w_T) summed over all of the tissue/organ exposed (i.e., $E = \Sigma w_T \times H_T$). The effective dose can give a broad indication of the level of detriment to health from radiation exposure because it allows the risk to the whole body to be expressed.[19] Effective doses resulting from each protocol were assessed statistically using 1-way ANOVA. A significant difference was considered to exist when $P < .05$.

RESULTS

The mean equivalent doses for the weighted tissues and organs that receive direct exposure during CBCT scanning and the effective doses derived using ICRP 2007 recommendations are shown in Table V. It should be noted that scans no. 5 and no. 11 used the same exposure factors and FOV and thus are a good measure of experiment reproducibility. Effective doses for scans no. 5 and no. 11 were 298 μSv and 306 μSv, respectively. This variation of 2.6% is similar to that reported in other studies.[15]

Figure 1 shows the calculated effective doses of scan protocol nos. 1-5: full FOV, normal resolution, and 5 different patient sizes. As the tube current increases, the effective dose increases proportionately. The coefficients of determination (R^2) between tube current and effective dose were 0.90 for both ICRP 1990 and ICRP 2007 calculations.

The mean effective doses of scan protocol nos. 5-9 (largest patient size, normal resolution, and 5 different FOVs) are shown in Fig. 2. If the volume height is restricted to the maxilla or mandible, the effective doses are reduced to 44% of the full volume height (which includes both jaws) for maxilla and 57% for mandible according to ICRP 2007 and 31% for maxilla and 55% for mandible according to ICRP 1990. If the volume diameter is limited to the anterior or posterior area only, the effective doses reduce to 42% and 66% (ICRP 2007) and 43% and 57% (ICRP 1990) of the full volume diameter which includes both anterior and posterior areas. Differences of effective dose derived using ICRP 2007 tissue-weighting factors among different FOV scans were statistically significant ($P < .05$), except for the comparison between maxilla and anterior ($P = .558$).

Figure 3 shows the comparison of the effective doses among the 3 protocols with different resolutions. Calculating with both ICRP 2007 and ICRP 1990 tissue-weighting factors, the effective dose of the examination with normal resolution was significantly higher than that with low-dose resolution ($P = .002$ [ICRP 1990] and $P = .003$ [ICRP 2007]). However, the effective dose of the examination with high resolution was essentially the same as that with normal resolution.

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

| | Fraction irradiated (%) | | | |
	Full FOV	Mandible	Maxilla	TLD ID
Bone marrow	16.5	5	5	
Mandible	1.3	1.3	0.7	13, 16, 17
Calvaria	11.8	2	2.6	1, 2, 3
Cervical spine	3.4	1.7	1.7	14
Thyroid	100	100	100	20
Esophagus	10	10	7	21
Skin	5	2	2	8, 9, 10, 15
Bone surface	16.5	5	5	
Mandible	1.3	1.3	0.7	13, 16, 17
Calvaria	11.8	2	2.6	1, 2, 3
Cervical spine	3.4	1.7	1.7	14
Salivary glands	100	100	100	
Parotid	100	100	100	11, 12
Submandibular	100	100	100	18, 19
Brain[a]	100	20	40	4, 5
Remainder				
Brain[b]	100	20	40	4, 5
Lymphatic nodes[a]	5	5	5	11-14, 16-19, 21
Muscle[a,b]	5	5	5	11-14, 16-19, 21
Extrathoracic airway[a]	100	100	100	6, 7, 11-14, 16-19, 21
Oral mucosa[a]	100	100	100	11-13, 16-19

[a]2007 recommendations of International Commission on Radiological Protection (ICRP).
[b]1990 recommendations of the ICRP.

Table IV. Current and previous International Commission on Radiological Protection tissue-weighting factors (w_T) for calculation of effective dose

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	Not applicable	0.01
Skin	0.01	0.01
Remainder tissues	0.05[a]	0.12[b]

[a]Adrenals, brain, upper large intestine, small intestine, kidney, muscle, pancreas, spleen, thymus, uterus.
[b]Adrenals, extrathoracic region, gall bladder, heart, kidney, lymphatic nodes, muscle, oral mucosa, pancreas, prostate, small intestine, spleen, thymus, uterus/cervix.

The no. 12 scan protocol stitches 3 horizontal views into 1 image, which can include most of the maxillofacial region. Owing to the automatic low-dose resolution setting, the calculated effective dose was 87 μSv (ICRP 2007) or 40 μSv (ICRP 1990).

DISCUSSION

The absorbed dose read from TLDs in the phantom depends on the position of the chips, skull size, and soft tissue morphology of the phantom, which simulate an actual human subject. The effective doses of the ProMax 3D calculated in the present study were lower than those reported previously by Ludlow et al.[11] A number of factors might have contributed to this difference, including differences in the anthropomorphic phantom (the phantom used in the work by Ludlow et al. was constructed with an actual skull; the phantom used in the present work was made from bone and soft tissue simulation materials) and differences in the location of TLDs (21 locations in the present study versus 24 locations in the study by Ludlow et al.). However, the greatest contribution to lower measured doses is likely an increase in copper filtration of the x-ray beam. The study by Ludlow et al. was based on an early version of the ProMax 3D unit. Beginning in 2008 units began to incorporate 0.5 mm of copper filtration to reduce dose. Patient dose is reduced by filtering lower-energy x-ray photons from the beam. An additional benefit of this approach is that the higher mean energy of the beam makes volume reconstruction less subject

Table V. Mean equivalent dose (μSv) to tissue/organs in the head and neck from ProMax 3D scannings and effective doses (μSv) derived using International Commission on Radiological Protection (ICRP) 2007 recommendations

| Scan no. | Bone marrow | Thyroid | Esophagus | Skin | Bone surface | Salivary glands | Brain[a] | Remainder tissues/organs | | | | | Effective dose |
								Brain[b]	Lymphatic nodes[a]	Extrathoracic region[a]	Muscles[a]	Oral mucosa[a]	
1	71	527	41	69	247	2,334	74	74	111	1,845	111	2,687	102
2	132	670	54	96	456	4,335	152	152	188	3,132	188	4,492	169
3	205	785	62	157	708	5,328	207	207	242	4,048	242	5,640	216
4	255	1,101	94	163	883	6,582	215	215	299	4,981	299	6,933	272
5	274	1,231	95	188	948	7,270	235	235	326	5,416	326	7,579	298
6	98	333	19	70	341	3,865	86	86	164	2,795	164	3,559	131
7	95	855	60	38	329	4,048	20	20	198	3,284	198	4,881	171
8	132	495	36	91	458	2,607	111	111	146	2,445	146	3,409	127
9	188	589	49	124	652	5,162	201	201	224	3,752	224	5,225	197
10	35	138	13	24	121	557	23	23	33	545	33	732	30
11	279	1,305	95	181	966	7,492	254	254	329	5,476	329	7,633	306
12	102	409	35	65	354	1,940	97	97	87	1447	87	1,868	87

[a]ICRP 2007.
[b]ICRP 1990.
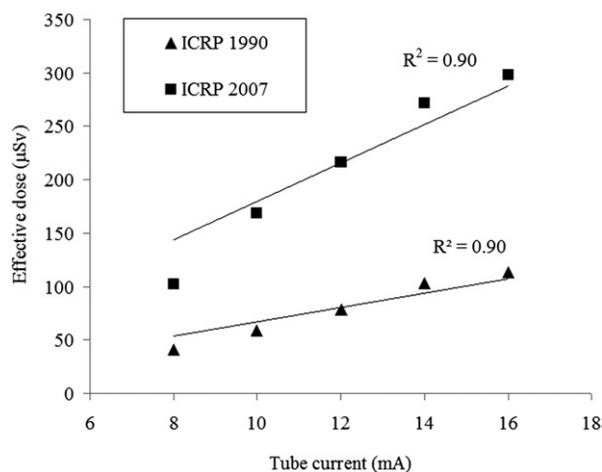
Fig. 1. Linear correlation between the calculated effective dose and tube current. *ICRP*, International Commission on Radiological Protection.
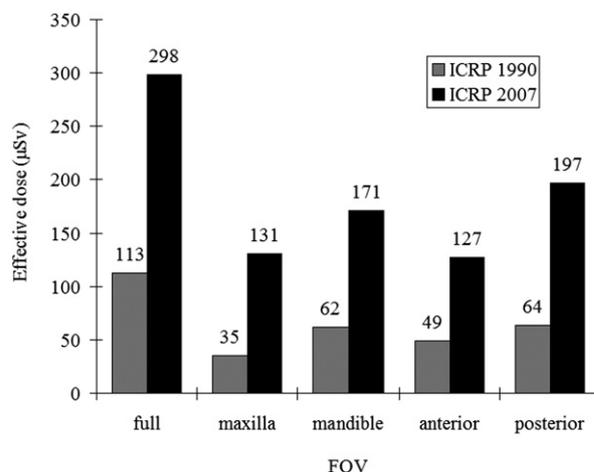
Fig. 2. Mean effective doses of the scan protocols for different fields of view (FOVs). *ICRP*, International Commission on Radiological Protection.

to beam-hardening artifact. Most pre-2008 units have now been retrofitted with additional filtration.

The ICRP periodically reassesses the risk of ionizing radiation by looking at new data from exposures of human populations. The ongoing evaluation of survivors of the atomic bomb explosions in Japan constitutes the single largest group where the long-term effect of radiation exposure has been studied. Tissue weights used in the ICRP 1990 formula for calculating effective dose were based largely on cancer mortality data. The 2007 tissue weights incorporate additional incidence and mortality data that have become available subsequent to the 1990 publication. In particular, cancer risks

in salivary glands and brain were judged to be sufficient to warrant weighting as individually named tissues. Inclusion of 3 new tissues in the remainder group (extrathoracic region, lymphatic nodes, and oral mucosa) in addition to increasing the weight of the remainder group from 0.05 to 0.12 has increased the proportion of total risk that is allocated to tissues in the maxillofacial region. Because the adjusted weights of the ICRP 2007 publication reflect additional evidence of cancer risks on soft tissues, this method should be used when calculating dose and risk in the maxillofacial region. We have also reported ICRP 1990 calculations of dose, so that the differences in dose between the 2 calculations can be fully appreciated.
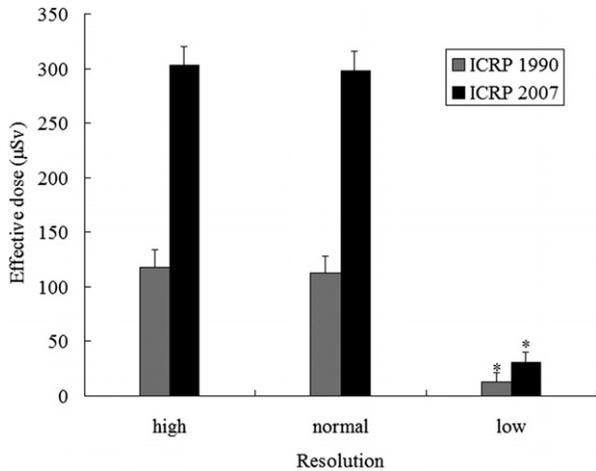
Fig. 3. Comparison of the effective doses among high, normal, and low resolutions. *ICRP*, International Commission on Radiological Protection. *Significant differences between low and high and between low and normal resolutions.

The net result of changes in the ICRP 2007 recommendations is a marked increase in calculated doses of the CBCT examinations of the maxillofacial region (Figs. 1-3). When the salivary glands are fully irradiated by the primary beam, such as during a full-FOV examination, the calculated effective dose for the ProMax 3D using the 2007 factors is more than double that using the 1990 factors. This is consistent with the findings of other studies for CBCT dosimetry measurements.[15,16,19]

Although full-FOV doses from the ProMax 3D CBCT with normal resolution were lower than the dose of helical CT examinations reported in the literature,[20] they were several to hundreds of times higher than the doses from single panoramic or other conventional dental radiographs. In particular, the standard FOV and largest patient settings resulted in mean equivalent doses for salivary glands of 7,381 μSv (average of scan nos. 5 and 11). Similarly, the mean equivalent doses measured in the extrathoracic region, which includes the nasal and pharyngeal airway mucosa, averaged 5,446 μSv for scan nos. 5 and 11. If applied for all imaging tasks and all patients, these scan protocols would result in a significantly higher patient dose than an approach which customizes exposure parameters for specific diagnostic tasks and patient characteristics. The ProMax 3D CBCT unit provides several dental application protocols that allow the clinician to reduce patient dose. Selectable patient size is one of these options. Default sizes provided by the manufacturer are proportional to the tube current (Table I). The effect of this on patient dose was demonstrated by the present study, with a significant reduction in dose achieved

when selecting the protocol for small patient size. Thus, when a patient with a small head is imaged, a "smaller" or "smallest" patient size should be selected. This is especially important for children who are twice as sensitive to radiation effects as adults.

Reducing the size of the FOV is another option that can reduce radiation dose. The ProMax 3D scanner employs collimation to provide different FOVs. The present study demonstrates that a small FOV contributes to lowering of effective dose. Scans collimated for the maxilla were able to dramatically reduce dose by eliminating direct exposure of the submandibular and thyroid glands (Fig. 2). Therefore, when the region of interest (ROI) is confined to the maxilla or mandible, it is helpful to choose an intermediate volume height focusing on the maxillary or mandible areas. If lesions (e.g., localized periapical or periodontal lesions) are limited to the anterior or posterior region, a half-volume diameter is recommended. In this case, the head of patient needs to be positioned accurately during scanning to ensure that the small FOV contains the ROI. The choice of FOV should be the smallest option that captures the ROI.

Another method to reduce radiation dose during CBCT examination is to lower the resolution settings. The ProMax 3D provides 3 levels of resolution: high, normal, and low. However, since the high- and normal-dose resolutions use the same exposure parameters, the equivalent dose and the calculated effective dose showed no difference. If the low-dose resolution is chosen, the present study shows that the effective dose can be reduced to about 10% of that with normal-dose resolution. Generally, a low dose leads to an image with low signal-to-noise ratio. Therefore, when a low-dose resolution is chosen to make CBCT images, the dental task at hand and required image quality should be taken into consideration. Further study is needed to evaluate the relationship between resolution settings and diagnostic accuracy for dental applications. For tasks where no difference in diagnostic accuracy is found between CBCT images taken with different resolution settings, the resolution resulting in reduced dose should be selected.

A new technology that the ProMax 3D uses is stitching to combine 3 volumes into a single larger volume to include all structures of the maxillofacial region. This is restricted to the low-dose resolution setting and thus produces an effective dose of 87 μSv (ICRP 2007) or 40 μSv (ICRP 1990), which is even lower than standard full-FOV scanning. This technique can be applied to evaluate extensive disorders, such as complex fractures or the bone destruction of odontogenic tumors. The effect of patient movement during the acquisition of the 3 volumes used for stitching and the effect of

lower resolution on diagnostic quality were not explored in the present study and should be addressed in future studies.

Although this study shows that the effective doses of the ProMax 3D are well below conservative limits recommended by the National Council on Radiation Protection and Measurements,[21] the practice of "as low as reasonably achievable" should guide us in selecting a dose that optimizes FOV and patient size. However, the CBCT technology develops quickly, and for newly released CBCT units, the referring dentist is often unaware of the availability of different scanning protocols. Therefore, a radiologist should be involved in devising the CBCT examination. This would help the technicians apply imaging procedures based on considerations of patient radiograph selection criteria, dose optimization, technical proficiency, and assessed diagnostic or treatment needs.[13] In addition, information on advanced imaging technologies should be included in the dental school curriculum and offered as continuing education updates so that users of this technology can appreciate the impact of technique choices on patient risk.

CONCLUSIONS

The ProMax 3D showed good reproducibility and was able to provide a wide range of radiation dose levels. Added beam filtration has significantly reduced examination doses of the Promax 3D CBCT scanner from previously reported effective doses. Choice of patient size, FOV, ROI, and resolution may affect patient dose by an order of magnitude. Thoughtful selection of each of these parameters is needed to optimize diagnostic information and to reduce patient dose.

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