RESEARCH ARTICLE

Evaluation of the effective dose of cone beam CT and multislice CT for temporomandibular joint examinations at optimized exposure levels

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Objectives: To compare the effective dose to patients from temporomandibular joint examinations using a dental CBCT device and a multislice CT (MSCT) device, both before and after dose optimization.

Methods: A Promax[®] 3D (Planmeca, Helsinki, Finland) dental CBCT and a LightSpeed VCT[®] (GE Healthcare, Little Chalfont, UK) multislice CT were used. Organ doses and effective doses were estimated from thermoluminescent dosimeters at 61 positions inside an anthropomorphic phantom at the exposure settings in clinical use. Optimized exposure protocols were obtained through an optimization study using a dry skull phantom, where four observers rated image quality taken at different exposure levels. The optimal exposure level was obtained when all included criteria were rated as acceptable or better by all observers.

Results: The effective dose from a bilateral examination was 184 µSv for Promax 3D and 113 µSv for LightSpeed VCT before optimization. Post optimization, the bilateral effective dose was 92 µSv for Promax 3D and 124 µSv for LightSpeed VCT.

Conclusions: At optimized exposure levels, the effective dose from CBCT was comparable to MSCT.

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Introduction

Diagnosis is crucial in every medical setting and at all levels of healthcare. Radiographic examination is an important diagnostic tool to assess morphological and structural alterations of the osseous components of the temporomandibular joint (TMJ).¹ The modalities used to evaluate TMJ bony changes include panoramic radiography, conventional tomography and CT, with helical or multislice CT (MSCT) or CBCT. MSCT

has been the modality of choice for evaluation of TMJ osseous changes. However, European guidelines, by SedentexCT, concluded that CBCT could be considered as an alternative to MSCT, if radiation dose from CBCT was shown to be lower.²

The two main technical differences between MSCT and CBCT that affect the radiation dose are the detector and the use of volume-of-interest imaging. Some early CBCT models used image intensifiers but newer models use flat-panel detectors. Flat-panel detectors have much smaller detector elements than

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conventional CT detector arrays, which allow for higher spatial resolution in CBCT images.^{3,4} Dental CBCT units use longer rotation times than conventional CT. This reduces the problems with scintillator afterglow, thus allowing the use of slower scintillator materials, such as caesium iodide (CsI), in CBCT.⁵ The columnar structure of CsI acts as a light guide, maintaining high spatial resolution even for thicker scintillator layers. This allows for detectors with both high sensitivity and high spatial resolution. Dental CBCT reconstructs three-dimensional (3D) volumes with isotropic voxels, usually between 0.1 and 0.3 mm in size.⁶ However, there are some drawbacks with flat-panel CT, such as reduced low-contrast resolution and lower detective quantum efficiency than conventional CT detectors.^{3,4}

The other major difference between dental CBCT and conventional CT is how the field of view (FOV) is defined. With medical CT, the diameter of a volume is fixed, covering a complete cross section of the head, and the scan length is adjustable, whereas CBCT devices have several pre-defined FOVs. The X-ray field may be collimated up to 3–4 cm in diameter in CBCT images, thus reducing the radiation dose to tissue outside of the FOV.

For all types of radiographic examinations, the radiation risk, in terms of effective dose to the patient, and the potential diagnostic benefit are two major aspects when considering the choice of the image modality. Most previous dosimetry studies on CBCT have been performed with FOVs in dentoalveolar or craniofacial region, and there is a lack of scientific reports regarding radiation dose from TMJ examinations. To our knowledge, no published study compares TMJ examination with both CBCT and MSCT, taking both effective dose and image quality into consideration. Since both medical MSCT and dental CBCT are commonly used for TMJ imaging, the present study aimed to compare the effective dose of one CBCT unit and one MSCT unit using their current clinical protocols for TMJ examination. Furthermore, the image quality at sequential exposure levels was assessed for CBCT and MSCT, in order to optimize exposure levels.

Methods and materials

A Promax[®] 3D (Planmeca, Helsinki, Finland) CBCT was used at 90 kV tube voltage and 8.0-mm aluminium half-value layer. This CBCT unit uses a 210° scan angle. For the MSCT unit, a GE LightSpeed VCT (GE Healthcare, Little Chalfont, UK) 64-slice CT at 120 kV tube voltage and medium bowtie filter (6.4-mm aluminium half-value layer) was used.

Dosimetry

Measurements were performed with TLD-100 thermoluminescent dosimeters (TLDs), read with a Harshaw 5500 (Thermo Scientific[™], Waltham, MA) TLD reader. The TLDs were calibrated for dose to water using the in-air method from the American Association of Physicists in Medicine protocol for 40- to 300-kV X-ray beam dosimetry.⁷ A Victoreen[®] Model 550-4-T (Victoreen, Cleveland, OH) ion chamber, calibrated at the Swedish Secondary Standard Dosimetry Laboratory, was used for the cross-calibration.

The effective dose was calculated by multiplying organ doses with the weighting factors from the International Commission on Radiological Protection (ICRP) publication 103, shown in Table 1.⁸ An Alderson Rando[®] (Alderson Research Laboratories, New York, NY) adult male anthropomorphic phantom was used to determine the organ dose. The TLD detectors were placed at 61 sites within the head and neck region, two detectors at each site. The mean reading of each detector pair was used when determining the organ dose. Consistency between detector readings was evaluated by interclass correlation (1,1), using SPSS[®] v. 22 (IBM Corporation, Armonk, NY). The number of measurement points for each organ is presented in Table 1. These sites were chosen to provide a good estimate of the mean dose to each organ of interest. The dose contribution to these organs from outside the head and neck region was assumed to be negligible. For organs only partially positioned inside the head and neck region, the measured organ doses were multiplied with the fraction of that organ which was irradiated, to obtain the mean organ dose. The fractions of active bone marrow positioned inside the cranium (7.6%),

Table 1 Mean organ doses, organ-weighting factors and effective dose for the CT and CBCT examinations pre optimization

Organ	Weighting factor ⁸	Dosimeter sites	Organ dose (μGy)	
			ProMax [®] 3D	LightSpeed VCT [®]
Active bone marrow	0.12	23	215	240
Endosteum	0.01	23	566	621
Brain	0.01	6	1018	1302
Oesophagus	0.04	2	15	20
Extrathoracic airways	0.12/13	7	1355	2349
Lymphatic nodes	0.12/13	17	119	98
Oral mucosa	0.12/13	6	710	1675
Salivary glands	0.01	12	2195	1681
Thyroid	0.04	5	183	234

LightSpeed VCT obtained from GE Healthcare, Little Chalfont, UK; ProMax 3D obtained from Planmeca, Helsinki, Finland.

mandible (0.8%) and cervical vertebrae (3.9%) were taken from Cristy.⁹ The fractions of endosteum (bone surface) inside the cranium (16.3%), mandible (0.4%), cervical vertebrae (2.1%) and the fraction of lymphatic nodes (6.3%) inside the head and neck region were applied according to ICRP 110.¹⁰ The fraction of the oesophagus inside the head and neck region was estimated at 10%. The contribution to the effective dose from the skin and muscle was considered negligible and was not included.

Doses to International Committee on Radiological Units four-component soft tissue were calculated and used for all organs examined, with conversion factors taken from the American Association of Physicists in Medicine protocol for 40–300 kV X-ray beam dosimetry.⁷ For the osteoprogenitor cells, the new definition of the surrogate tissue was used according to ICRP 110.¹⁰ In addition, the terminology of “endosteum” was applied instead of the obsolete “bone surface”, according to ICRP 116.¹¹ Dosimetry of active bone marrow and endosteum is complicated owing to the complex anatomical structure inside the spongiosa. In the tissue close to the trabecular bone, there will be a contribution of additional electrons from the bone into the endosteum and active marrow, resulting in a higher dose. To account for this increase, we multiplied dose to the soft tissue with dose enhancement factors calculated by Johnson *et al*,¹² as an approximation of the interface effects. The dose enhancement factors were calculated by interpolating from the values tabulated for different energies by Johnson *et al* and combining these values with simulated X-ray spectrums for both devices (Table 2).

For both the CBCT and the MSCT units, the effective dose was determined based on our clinically used exposure protocols. For CBCT, the manufacturer-recommended settings were used, whereas for MSCT exposure parameters optimized by the Karolinska University Hospital were used. A lateral scout image was included for MSCT, and two scout images, frontal and lateral, were included for CBCT. The following exposure parameters were used for Promax 3D: 90 kV tube voltage, 12 mA tube current, 12 s exposure time with a 4×5 cm cylindrical FOV, resulting in a dose–area product of 606 mGy cm^{-2} . For LightSpeed VCT, the following parameters were used: a helical scan with 120 kV tube voltage, 73 mA tube current, 0.5 s rotation time, 0.969 pitch with

a scan length of 3 cm, resulting in a volume CT dose index of 7.42 mGy and a dose–length product of $38.26 \text{ mGy cm}^{-1}$.

Dose optimization

In order to establish optimized exposure levels, a simple image quality assessment study was performed at different exposure levels. For this part of the study, a different anthropomorphic phantom was used, comprising a human dry skull inside simulated soft tissue, shown in Figure 1. Images of the phantom’s right TMJ were acquired at five levels of tube current, with all other parameters identical to the dosimetric study. For the MSCT, tube currents between 90 and 50 mA, with an interval of 10 mA, were used. Iterative reconstruction was not used. For CBCT, tube currents between 4 and 12 mA, with an interval of 2 mA, were used. For both modalities, the sagittal and coronal slices were reconstructed through the long axis of the condyle. The voxel sizes were 0.16 mm for CBCT images and $0.293 \times 0.293 \times 0.625$ mm for MSCT images. All the slices were eventually viewed with 1-mm thickness in order to be comparable between the two types of images.

Four dentomaxillofacial radiologists assessed the image quality in terms of how well they could identify the intra-articular joint space, the cortical bone and the trabecular bone of the TMJ, as well as the subjective experience of noise level in the images. All the questions were assessed on a one to three scale, with three being excellent, two being acceptable and one being unacceptable. The optimized exposure level was defined as the lowest possible level where all observers rated all four criteria as at least acceptable. Apart from these optimization criteria, the observers subjectively rated the overall image quality for each image on the same one to three scale. Two sets of images, CBCT and MSCT separated, were randomly displayed; both sets using the same model of monitor (RadiForce MX191; EIZO, Hakusan, Japan), with a built-in digital imaging and communications in medicine setting. The radiographs were evaluated under dimmed room light and a viewing distance of about 50 cm. The observers were allowed to adjust the window setting for light intensity and contrast according to their own preferences. The CBCT stacks were assessed using the Romexis[®] software (Planmeca), while the MSCT images were assessed using the Sectra PACS (Sectra AB, Linköping, Sweden).

Table 2 Dose enhancement factors for active bone marrow and endosteum in different bones for the X-ray spectra of the two devices. Calculations based on the method and simulations of Johnson *et al*¹²

Organ	ProMax [®] 3D		LightSpeed VCT [®]	
	Active marrow	Endosteum	Active marrow	Endosteum
Cranium	1.216	1.727	1.192	1.671
Mandible	1.017	1.796	1.014	1.747
Cervical vertebrae	1.113	1.736	1.102	1.679

LightSpeed VCT obtained from GE Healthcare, Little Chalfont, UK; ProMax[®] 3D obtained from Planmeca, Helsinki, Finland.

Figure 1 Anthropomorphic phantom used for image quality assessment: (a) photograph of the phantom, (b) multislice CT slices at 80 mA and (c) CBCT slices at 6 mA.

Results

Table 1 shows the mean organ doses, organ-weighting factors and their corresponding effective dose before dose optimization for the unilateral CBCT and bilateral MSCT TMJ examination. Interclass correlation was 0.999 and 0.998 for CBCT and MSCT, respectively. The LightSpeed VCT examination resulted in higher organ doses for all organs except the salivary glands and lymphatic nodes, with a 20% higher effective dose than one Promax 3D examination. However, if both TMJs should be examined, the resulting effective dose from Promax 3D would be

184 μ Sv, which is 60% higher than that from LightSpeed VCT examination.

By applying our image quality assessment criteria, the optimized exposure levels were 6 mA for Promax 3D and 80 mA for LightSpeed VCT. Therefore, the estimated effective dose using the optimized exposure parameters were 92 μ Sv for a bilateral Promax 3D examination and 124 μ Sv for a LightSpeed VCT. Figure 2 demonstrates the overall assessment of image quality based on four observers at different exposure levels for CBCT and MSCT, respectively. At optimized exposure levels, the rating of the overall image quality by Observers 1–4 was 3, 3, 2 and 3 for CBCT and 3, 2, 2 and 2 for MSCT.

Figure 2 Overall assessment of image quality for multislice (MSCT) and CBCT, based on four observers.

Discussion

Most of the published studies on effective doses from CBCT considered the FOVs in the dental alveolar or large craniofacial region. The present study focuses on TMJ examinations, irradiating a different area, as well as using both higher kilovoltage and smaller FOV compared with most dental studies. Librizzi et al¹³ reported the effective dose from bilateral TMJ examination using a different CBCT device, CB MercuRay (Hitachi Medical, Twinsburgh, OH), resulting in 550 μ Sv for either one 9-inch FOV or two 6-inch FOVs. Lukat et al¹⁴ reported an effective dose of 220 μ Sv from a CB MercuRay using a 9-inch FOV, and 20 μ Sv from a Kodak 9000 3D (Carestream, Rochester, NY) CBCT using two 5.0×3.7 cm FOVs. The difference between the effective doses determined for CBCT and MSCT in the present study, 92 and 124 μ Sv, respectively, were minor compared with the very large range of effective doses from CBCT examinations of the TMJ in the literature, 20–550 μ Sv. The large difference in effective dose from different CBCT models is partly owing to the FOV used. A wide range of FOVs for different diagnostic purposes is important for dose optimization. For bilateral TMJ examination, we recommend either a FOV of at least 12 cm width but no more than 5 cm height, or the use of two small FOVs about 4×4 cm in size. Owing to the lack of suitable FOVs, some CBCT models might be, from a dose perspective, unsuitable for TMJ examinations. In the case of CB MercuRay with 9-inch FOV, there is also a large difference in effective dose between studies, owing to different exposure protocols being used. Owing to the large range of reported effective doses and large technical differences between the CBCT models, dose comparison between CBCT and MSCT for TMJ diagnostics is complex. Currently, there is not enough evidence in the literature to declare that one modality gives lower doses than the other. The data seem to indicate that dose optimization, in forms of suitable FOVs and optimized exposure parameters for various diagnostic tasks, is equally or more important than the choice of CT modality.

The authors want to stress the importance of taking into consideration diagnostic tasks and image quality when comparing effective doses between different modalities. Optimization studies have shown a large potential for dose reduction in both dentomaxillofacial MSCT and CBCT examinations.^{15–17} Dawood et al¹⁵

studied the potential for dose reduction from 68 patients undergoing pre-implant evaluation with CBCT. In their study, low-dose protocols, down to 12.5% of the manufacturers' standard value, were used with no significant difference in the surgeons' confidence in judging bone height and bone width. TMJ diagnosis is more sensitive to noise than implant planning and would thus be expected to require a higher dose. The present study indicates a potential dose reduction of up to 50% for TMJ imaging using Promax 3D, compared with the manufacturer's recommended exposure parameters.

The *de facto* standard detector placement for effective dose measurements in the dental field, using 24 measurement points, was introduced by Ludlow et al¹⁸ in 2006. However, in 2010, Pauwels et al¹⁹ used 150 measurement points and showed that measurements at 24 points provided insufficient accuracy, especially for small FOVs, such as the ones suitable for TMJ imaging, with organ doses deviating up to 80%. In the present study, we reduced the measuring points to 61, mostly by eliminating points at organs with no or negligible contribution to the effective dose, such as the eyes, skin and muscle.

Our dosimetric method included dose enhancement factors for active bone marrow and endosteum, correcting for the influence of the nearby trabecular bone. These corrections are usually not included when measuring organ doses. However, since the cranium has the highest active bone marrow dose enhancement factors of all bones and a considerable portion of the effective dose, about 25% in the present study, came from the active marrow, this correction was initially deemed relevant to perform. Still, the correction affected only the effective dose with 7.5% for Promax 3D and 6% for LightSpeed VCT, a difference that was minor when considering the uncertainties in determining the effective dose from TLD measurements. Thus, owing to the comparatively small influence on effective dose, it is not essential to perform the relatively difficult correction for the influence of the trabecular bone.

In conclusion, the effective doses determined for the Promax 3D CBCT and LightSpeed VCT MSCT, 92 and 124 μ Sv, respectively, were comparable. There seemed to be a large potential for dose reduction compared with the manufacturers' standard values; in our case, 50% for CBCT. The use of appropriate FOV and optimized exposure parameters are essential for obtaining a low effective dose.

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