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Comparative study of image quality and radiation dose of cone beam and low-dose multislice computed tomography - an in-vitro investigation

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Abstract

Objectives The aim of this study was to evaluate the image quality and dose exposition of different cone-beam computed tomography (CBCT) and low-dose multislice spiral CT (MSCT) scanners.

Materials and methods A human cadaver head was examined with three MSCT and five CBCT scanners. The radiation dose was measured using an Alderson RANDO phantom. Standard protocols were used to obtain the CBCT data. For the MSCT devices, the tube voltage and tube current were modified to obtain acceptable image quality while keeping the radiation dose as low as possible. The image quality of MSCT and CBCT devices was determined by examining the enamel–dentin and dentin–pulp interface and the periodontal ligament space of 22 teeth.

Results Inter- and intra-observer agreement was found for the different groups of raters. CBCT systems were rated superior to MSCT devices in terms of image quality for all dental structures. The differences in image quality among the studied CBCT and MSCT scanner groups did not turn out to be significant but were significant between CBCT and MSCT devices. The organ dose varied considerably between the different CBCT and MSCT devices. The differences concerning the organ dose were notably pronounced in the area of the eye lens.

Conclusions The tested devices exhibited significant differences with respect to the organ dose. The variance was particularly pronounced in the CBCT devices. With a dose exposition equal or lower than the CBCT, the image quality in the MSCT devices was judged to be significantly worse.

Keywords Multislice computed tomography · Cone-beam computed tomography · Radiation dosage · Image quality

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Introduction

Sectional imaging is an essential component not only for the medical assessment of teeth and the surrounding bone but also for the therapy planning of pathologies of the viscerocranium and the interdisciplinary treatment planning in orthodontics and oral/maxillofacial surgery.

High-resolution three-dimensional overlap-free representation for complex medical problems has usually been carried out by means of multislice computed tomography (MSCT) [1]. With cone-beam CT (CBCT), a new imaging modality is increasingly being used in dental imaging [2–7]. In CBCT, a small C-arm-type tube detector configuration is rotated around the patient's head. The scan geometry results in a scanning range with a more restricted field of view (FOV) than in MSCT. The size of the cylindrical FOV can vary from small fields for the imaging of selected teeth to larger fields for the imaging of the entire craniofacial area [8, 9]. In the past, various studies have concerned themselves with various CBCT scanners, whose advantage over conventional MSCT

devices—that the effective radiation exposure for the patient is up to 15 times lower [10–12] with a comparable diagnostic value—was confirmed [6, 7, 9, 13–15]. The lower effective dose is due to technical features of CBCT devices, such as cone-beam geometry, low tube current values, and detector properties [16]. Furthermore, the cone-beam technique provides a rapid decrease in the dose from the area of the primary beam to the direct vicinity with a relatively clear delineation to scatter radiation [17]. Only a few studies have dealt with the comparison of image quality in dental MSCT and CBCT devices. Such comparisons were usually based on patient data [2, 8, 15, 18]; more rarely, test specimens and phantoms have been used [19, 20]. In the previous studies, however, very different protocols were usually used in the comparison of MSCT and CBCT devices, which do not permit a fair comparison. While little can be changed in the settings of CBCT devices, MSCT scanners offer the radiologist the ability to precisely adapt the scan parameters to the diagnostic problem, which can have a substantial influence on the dose.

Kyriakou et al. [20] compared different CBCT scanners in their standard settings with a low-dose MSCT and determined that a reduction of the effective dose—even below the level of a CBCT examination—was possible without sacrificing image quality. However, it is important to bear in mind that this is only valid for CBCTs with large fields and relatively high exposure. In the study by Kyriakou et al. [20], the image quality was assessed using various physical phantoms. The aim of our study was to evaluate the image quality on the basis of a complete human cadaver head, taking into account very fine-scale dental structures. Furthermore, the organ doses of the five studied CBCT units with standard settings and three MSCT devices with customized investigation parameters were to be compared.

Methods

Skull phantom

A fresh frozen cadaver head of a female Caucasian adult, provided by the Institute of Anatomy, xxxx, was used as a phantom for imaging by various CBCT and MSCT scanners. The tooth status of the patient revealed filling-free teeth as well as different metal crowns and fixed partial dentures in the upper and lower jaw. The number of teeth totaled 22. All the upper teeth (three molars, two premolars, two canines, and four front teeth) as well as two molars and one premolar in the lower jaw had metal crown restorations; apart from that, the other teeth (two premolars, two canines, and four front teeth) in the lower jaw had no restoration at all. All teeth were evaluated separately to compare the image quality of the different CBCT and MSCT scanners.

Radiation dose assessment

Radiation exposure was determined using an anthropomorphic head and neck Alderson RANDO (The RANDO® Phantom, Alderson Research Laboratories Inc., Stamford, CT, USA). This phantom consists of a human skull embedded in an isocyanic rubber equivalent to human soft tissues in terms of the anatomic number and a specific density of 0.985 g/cm^3. Absorption and spread regarding radiation match that of human tissue. The phantom consists of ten axial sections with a thickness of 2.5 cm; each section is provided with holes in which lithium fluoride thermoluminescent dosimeters (LiF-TLDs; The Harshaw Chemical Company, Crystal and Electronics Products Department, Solon, OH, USA) were inserted (TLD-100 rods, diameter 1 mm, height 6 mm). For all examinations, sections 0 to 9 were equipped with TLDs. TLDs were placed at specific anatomical positions to define the radiation dose of the level of the TLD locations of selected organs (cerebrum, eye lens, thyroid gland, etc.). All dosimeters were gauged with the corresponding radiation quality. Thirty-six TLDs were positioned at 13 defined organ regions (Table 1) for each measurement (~3 TLDs per organ). Within 15–18 h after exposure, the readout of the thermoluminescent dose values was obtained with a UD 505 A TLD reader (Matsushita Electric, Osaka, Japan). In order to measure above the detection limit of the TLDs, the phantom was exposed three times and the resulting values were divided by 3. The organ dose results were the average value of the evaluated data of the three TLD rods per measuring point. Dose values (in milligray) were calculated by applying a calibration factor of 0.47 mGy/nC. Thereby, the light emission (measured in coulomb) of each individual LiF-TLD was evaluated by the readout device and multiplied with the calibration factor. The calibration factor was measured by applying a well-

Table 1 TLD number, section, and irradiated tissue of the head and neck Alderson Phantom

TLD number	Section	Tissue
1a–1b	1	Cerebrum
2a–2c	1	Frontal cerebrum
3a–3c	2	Bone surface
4a–4c	2	Cerebrum left
5a–5c	2	Cerebrum right
6a–6c	2	Frontal cerebrum
7a–7c	3	Cerebellum
8a–8c	3	Cerebrum
9a–9b	3	Eye lens left
10a–10b	3	Eye lens right
11a–11c	4	Cerebellum
12a–12c	8	Thyroid gland
13a–13c	9	Thyroid gland

defined radiation exposure under laboratory conditions. No organ fractions where used throughout the whole evaluation. The individual LiF-TLD positions were weighted equally.

Imaging systems

The following CBCT scanners were evaluated: 3D Accuitomo 170 (J. Morita Inc., Japan), 3D eXam (KaVo Dental GmbH, Germany), Pax Zenith 3D, Pax Reve 3D, and Picasso Trio 3D (E-Woo, South Korea). Standard protocols recommended by the manufacturer were used with all CBCT units (Table 2). Some scanners offered additional parameters to increase the radiation dose (i.e., for reducing metal artifacts or for high resolution), but these dedicated protocols were disregarded. The head and the RANDO® phantom were positioned using the built-in laser orientation guide in each unit so that the occlusal plane was parallel to the scan plane in the center of the scan field. MSCT scanning was performed on a 10-, 64-, and 128-slice CT system (SOMATOM Sensation 10, SOMATOM Sensation 64, SOMATOM Definition Flash; all from Siemens Healthcare, Forchheim, Germany) to represent different generations of MSCT systems (Fig. 1, Table 3). Anatomy-based online tube current modulation was used as appropriate. An identical reference tube current, tube voltage, rotation time, and pitch factor were employed with the goal of attaining the lowest possible radiation dose. Because minimum slice thickness varied between the MSCT systems, all raw data were reconstructed uniformly with 0.75 mm every 0.3 mm using a bone kernel (H 60 s).

Data transfer and image quality assessment

The volume data sets were stored in DICOM format. Since not all data sets could be transferred to our regular PACS viewer because of inconsistencies of the DICOM format, the data sets were evaluated on a dedicated 3D workstation using the software OsiriX v5.0.0 (OsiriX). The workstation was connected with a 2-megapixel grayscale monitor (RadiForce® GX240, EIZO Nanao AG, Wädenswil, Schweiz), and MPR,

windowing (center/WW), and zooming were freely available. The window level sets were optimized before analysis for each different data set and could be manipulated during the assessment at the reader's discretion. For image quality evaluation, the method proposed by Holberg et al. [3] and Liang et al. [15] was used (Tables 4 and 5). The data sets were evaluated in consensus by two experienced observers (one dentist and one radiologist, group 1). Two additional observers analyzed image quality in a separate reading session to test for reproducibility of the results (groups 2 and 3). The evaluation of the data took place on two different examination days, which were separated by an interval of at least 4 weeks. All observers were highly experienced in the analysis of CBCT and MSCT scans and were blinded to all image acquisition details. The image quality of five different dental and periodontal structures (Table 5) was assessed.

Statistical analysis

The image quality was measured by the raters using an ordinal performance scale with five levels (Table 5). This scale was used for all five dental and periodontal parameters as the enamel–dentine junction; the dentine–pulp border; and the cervical, middle, and apical thirds of the periodontal space (Table 4). A generalization of Cohen's kappa coefficient (iota coefficient) was used to estimate the agreement between raters (inter- and intra-rater agreement) [21, 22]. The iota coefficient is a generalization of Cohen's kappa to multiple raters and multiple outcome variables (here, the five dental and periodontal structures). Because it is essentially a weighted average of pairwise kappa values, the range of the iota coefficient is the same as for Cohen's kappa. Specifically, it equals 1 if agreement between raters is perfect. Conversely, an iota value of 0 indicates agreement expected by chance. Interested readers are referred to reference [22] for a detailed mathematical derivation of the iota coefficient. For each of the eight devices, the image quality was summarized using descriptive statistical methods such as arithmetic means, medians, and standard deviations.

Table 2 Overview of CBCT and selected scan parameters

System	Detector	Tube voltage (kV)	Tube current (mA)	Height of scan volume (mm)	Diameter of scan volume (mm)	Scan time (s)	Voxel size (mm)	Manufacturer
3D Accuitomo 170	Flat panel (aSi)	80	7	120	170	18	0.125 isotropic	J. Morita Inc., Japan
3D eXam	Flat panel (aSi)	120	5	230	170	8.5	0.3 isotropic	KaVo Dental GmbH, Germany
Pax Zenith 3D	Flat panel (CMOS)	95	7.3	140	160	24	0.2 isotropic	E-Woo, South Korea
Pax Reve 3D	Flat panel (CMOS)	85	6.5	150	150	24	0.2 isotropic	E-Woo, South Korea
Picasso Trio	Flat panel (CMOS)	85	5.5	70	120	15	0.2 isotropic	E-Woo, South Korea

Fig. 1 Presentation of the assessed dental and periodontal structures (Table 3). **a** 3D Accuitomo 170 (J. Morita Inc., Japan), **b** 3D eXam (KaVo Dental GmbH, Germany), **c** Pax Reve 3D, **d** Pax Zenith 3D, **e** Picasso Trio (all from E-Woo, South Korea), **f** SOMATOM Definition Flash, **g** SOMATOM Sensation 10, and **h** SOMATOM Sensation 64 (all MSCT devices were from Siemens AG, Healthcare Sector, Germany)
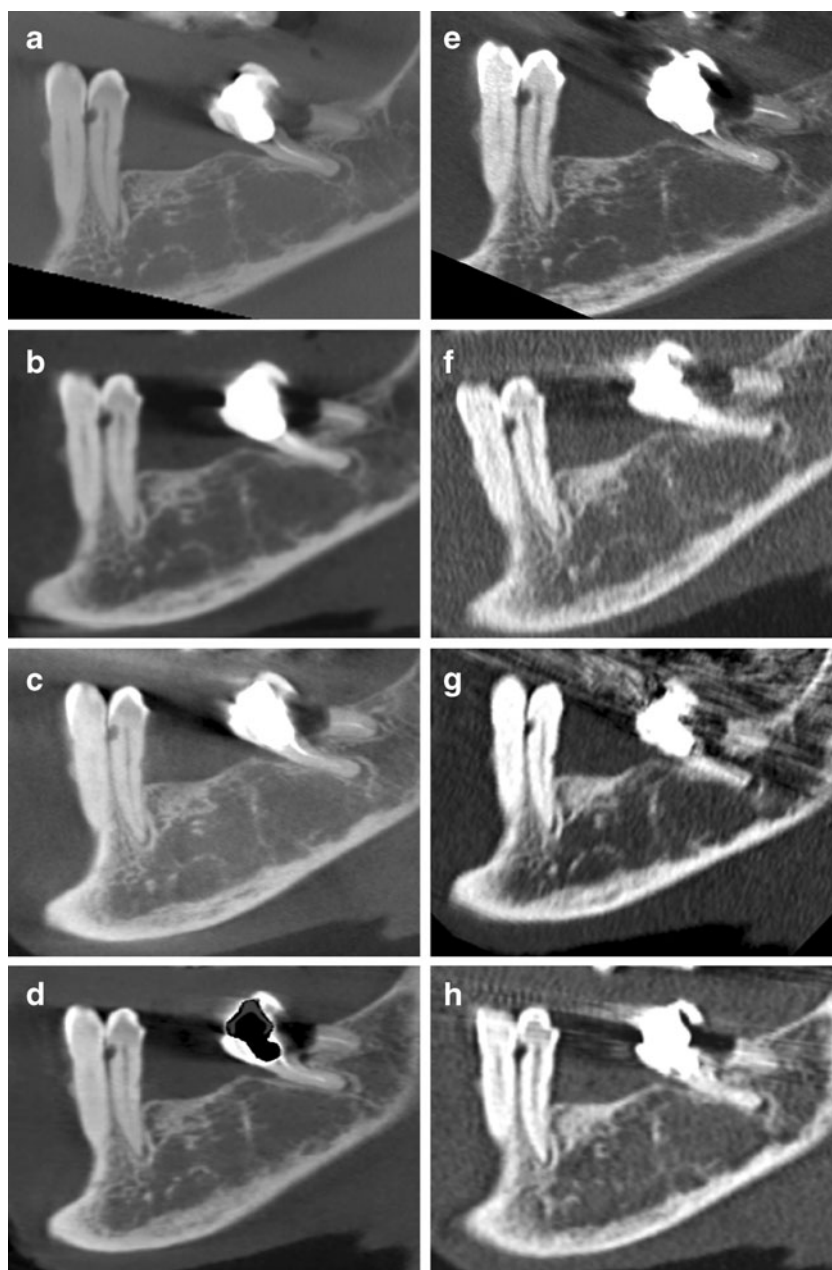
Friedman tests were used to detect significant differences between the image quality ratings obtained from the MSCT and CBCT devices.

Significant results obtained from the Friedman test indicated that some of the devices showed significant differences in image quality. On the other hand, the Friedman test does not provide information about which devices are different but merely indicates that there is some difference in scoring. Therefore, in order to assess which pairs of devices showed significant differences in image quality, Wilcoxon–Nemenyi–McDonald–Thompson tests were applied [23]. p values of this procedure were adjusted for multiple comparisons. A two-sided significance level of 0.05 was used for all hypothesis tests.

Results

Inter-rater agreement

Agreement between the different groups of raters was substantial according to Landis and Koch [24] (iota coefficient of group 1 versus group 2: $k_{1/2}=0.88$, 95 % confidence interval [0.48, 0.92]; iota coefficient of group 1 versus group 3: $k_{1/3}=0.87$, 95 % confidence interval [0.47, 0.89]; iota coefficient of group 2 versus group 3: $k_{2/3}=0.83$, 95 % confidence interval [0.40, 0.90]). This result guaranteed the comparability of image quality ratings even if they were obtained from different raters. Average kappa values for the parameters were 0.788 (group 1 versus group 2, median 1),

Table 3 Overview of MSCT and selected scan parameters

System	Tube voltage (kV)	Reference tube current (mA)	Height of scan volume (mm)	Diameter of scan volume (mm)	Pitch	Scan time (s)	Rotation time (s)	Reconstructed slice thickness (mm)	CTDI (mGy)	Voxel size (mm)	Manufacturer
SOMATOM Sensation 10	80	35	150	500	0.9	18.1	0.5	0.75	2.88	0.29	Siemens AG, Healthcare Sector, Forchheim, Germany
SOMATOM Sensation 64	80	35	150	500	0.9	4.61	0.5	0.75	1.60	0.29	
SOMATOM Definition Flash	80	35	150	500	0.9	2.88	0.5	0.75	1.52	0.29	

0.71 (group 1 versus group 3, median 0.93), and 0.67 (group 2 versus group 3, median 0.78).

Intra-rater agreement

Concerning the intra-rater agreement, the agreement was very high and could be rated as almost perfect according to Landis and Koch [24] (iota coefficient of group 1: 0.998, 95 % confidence interval [0.995, 1]; iota coefficient of group 2: 0.995, 95 % confidence interval [0.946, 0.998]; iota coefficient of group 3: 0.998, 95 % confidence interval [0.971, 1]) Mean kappa values were 0.980 (group 1, median kappa 1), 0.9 (group 2, median kappa 1), and 0.959 (group 3, median kappa 0.78).

Image quality

The results obtained from the descriptive statistical analysis are summarized in Table 6. Image quality for all CBCT systems were rated higher than for MSCT. This result was uniformly observed in all five examined dental and periodontal variables. While the average quality ratings obtained from the CBCT ranged between 3.00 and 4.86 (moderate to excellent quality), the corresponding ratings obtained from the MSCT ranged between 1.55 and 2.63 (insufficient to moderate quality). The results obtained from the descriptive statistical analysis were further confirmed by the graphical analysis presented in Fig. 2. Within the group of MSCT devices, the best image quality was obtained from the SOMATOM Definition Flash (mean values between 2.33 and 2.63) while the worst image quality was obtained from the SOMATOM Sensation 10 (mean values between 1.55 and 2.02). Again, this result was uniformly observed in all five dental and periodontal parameters.

For all outcome variables, Friedman tests resulted in p values smaller than 0.001, suggesting that the devices differed significantly in image quality. Pairwise comparisons of the eight devices revealed that the SOMATOM Sensation10 and Sensation 64 performed significantly worse than the five CBCT devices (adjusted p values of Wilcoxon–Nemenyi–McDonald–Thompson tests <0.05, Table 7). This result was obtained for all dental and periodontal parameters. Differences between the SOMATOM Definition Flash (being the best of the examined MSCT devices) and the CBCT devices were not found to be uniformly significant. Nevertheless, most of the pairwise comparisons between the SOMATOM Definition Flash and the CBCT devices resulted in significant differences in image quality.

Organ dose

The measured organ doses at the level of the TLD locations of the different irradiated organs in the RANDO phantom

Table 4 Definition of the assessed dental and periodontal structures

Anatomical structure (abbreviation)	Definition
Enamel–dentine junction (ED)	Junction between enamel and dentine
Dentine–pulp border (DP)	Border between dentine and pulp chamber
Cervical third of the periodontal space (PS cervical)	Cervical portion of the 0.2-mm-wide gap between tooth root and alveolus
Middle third of the periodontal space (PS medial)	Medial portion of the 0.2-mm-wide gap between tooth root and alveolus
Apical third of the periodontal space (PS apical)	Apical portion of the 0.2-mm-wide gap between tooth root and alveolus

are presented in Table 8 together with the irradiated tissue. The 3D Accuitomo 170 showed the highest dose for the TLDs located in the area of the brain and the eye lens (TLD levels 1–4, see Table 1), whereas for all organs considered in this study, the Picasso Trio displaced the lowest doses for the irradiated organs. Concerning the dose for the TLDs located in the area of the thyroid gland (TLD levels 8–9), the discrepancy between the chosen devices was enormous. The highest dose was measured for the Pax Reve 3D (2.78 mSv), with the SOMATOM Sensation 64 (2.12 mSv) concisely below. All the other devices displayed a distinctly lower dose (0.43–1.54 mSv).

Discussion

The objective of this study was to compare the image quality and the radiation dose of CBCT images using standard settings with deliberately strongly reduced low-dose MDCT devices. While numerous studies comparing the image quality or dose of CBCT and MSCT devices in standard protocols exist [2, 5, 8, 15, 16, 18, 19, 25], only a few investigators [16, 20, 26] have addressed the comparison of the image quality of CBCT devices with low-dose MSCT devices. Only Kyriakou et al. [20] used the method of investigating the image quality of both types of devices at the same dose levels (CT dose index, CTDI). In this case, the dose measurement was performed in an ionization chamber in a cylindrical PMMA phantom; the image quality was examined using established phantoms to determine the spatial resolution, the contrast behavior, and the pixel noise. Since the physical principles have been studied exhaustively using phantoms [20], we decided on a method of examination that was as practical as possible. Due to reasons of radiation hygiene, the implementation of the various procedures is forbidden in living subjects. Since anatomical conditions influence the weakening of the X-rays and thus the image quality [6], we decided to use a freshly frozen complete human cadaver head as the subject of our investigation.

Image quality

With regard to the representation of skeletal structures, numerous studies indicate that CBCT devices have high imaging precision; significant differences have been found between different CBCT device types [2, 9, 15, 18, 19, 27–30]. This is also in agreement with our experience: In terms of the investigated dental and periodontal parameters, there were marked differences in image quality within the group of CBCT devices; however, these did not prove to be statistically significant. The same is true for the group of MSCT devices. But the difference between the individual CBCT systems and the strongly low-dose MSCT examinations did prove to be significant. This is shown by clear differences within the groups with respect to image quality. The observed significances were found to be independent of the examined anatomic structure and were correlated solely with the corresponding device. To keep the dose to a minimum in the MSCT investigations, a very low tube voltage (80 kV) was deliberately used under experimental conditions. This accepted the fact that the low tube voltage results in an increase in image noise, which explains the relatively insufficient image quality compared to the CBCT devices in the assessment of extremely fine structures such as the periodontal ligament. The delineation of very dense materials such as dentine and enamel deteriorates drastically at low kilovolt values. The image quality can be significantly improved by using higher energy X-rays, but at the expense of the dose. The nominal voxel size in the present study was 0.29 mm for the MSCT data sets and 0.125 mm (3D Accuitomo 170) to 0.3 mm (3D eXam) for the CBCT data

Table 5 Rating of the image quality evaluation

Rating	Description
Score 1	Insufficient image quality
Score 2	Poor image quality
Score 3	Moderate image quality
Score 4	Good image quality
Score 5	Excellent image quality

Table 6 Summary of image quality ratings for the different anatomical parameters

		3D Accuitomo 170	3D eXam	Pax Reve 3D	Pax Zenith 3D	Picasso Trio	SOMATOM Sensation 10	SOMATOM Sensation 64	SOMATOM Definition Flash
Enamel–dentine border	Mean (±SD)	3.46±1.18	3.08± 1.46	3.02± 1.26	3.28±1.31	3.29±1.3	1.68±0.95	1.91±0.92	2.61±0.69
	Median (range)	3 (2–5)	2.5 (1–5)	3 (1–5)	3 (2–5)	3 (2–5)	1 (1–3)	2 (1–4)	2.5 (2–4)
Dentin–pulpal border	Mean (±SD)	4.21±0.66	3.7±1.01	3.94±0.9	3.59±1.05	4.59± 0.71	1.55±0.67	2.23±0.81	2.63±0.84
	Median (range)	4 (3–5)	4 (1–5)	4 (2–5)	4 (1–5)	5 (2–5)	1 (1–3)	2 (1–4)	2 (2–4)
Cervical third of the periodontal space	Mean (±SD)	4.45±0.85	3.67±1.13	3.8±1.14	3.61±1	4.27± 1.28	1.71±0.82	1.83±0.72	2.33±0.56
	Median (range)	5 (2–5)	4 (1–5)	4 (1–5)	4 (1–5)	5 (1–5)	1.5 (1–3)	2 (1–3)	2 (2–4)
Middle third of the periodontal space	Mean (±SD)	4.5±0.86	3.64±1.1	4.08± 0.74	3.61±1	4.5±0.91	1.76±0.85	2.05±0.67	2.41±0.67
	Median (range)	5 (2–5)	4 (1–5)	4 (3–5)	4 (1–5)	5 (2–5)	1.5 (1–3)	2 (1–3)	2 (2–4)
Apical third of the periodontal space	Mean (±SD)	4.83±0.37	4.12± 0.71	4.25± 0.64	4.19±0.58	4.86± 0.35	2.02±0.92	2.27±0.72	2.52±0.69
	Median (range)	5 (4–5)	4 (3–5)	4 (3–5)	4 (3–5)	5 (4–5)	2 (1–3)	2 (1–4)	2 (2–4)

The table contains means, standard deviations (SD), medians, and minimum and maximum values of the ratings

sets. The voxel size of the devices used apparently did not have a direct influence on the image quality results, which agrees with the results of Damstra et al. [31]. Kyriakou et al. [20] found that CBCT devices supply significantly more inhomogeneous images than MSCT devices. A further study found that another disadvantage of CBCT devices is the insufficient calibration of the CT values, which prevents quantitative assessments of bone density [32]. Causes for this include physical effects such as hardening, scattered radiation, and detector weaknesses [20].

CBCT radiation dose

As has already been observed by Pauwels et al. [33], the differences in the organ dose depending on the type of instrument used among the investigated CBCT scanners were striking. A direct comparison of the absolute values of the organ dose between the different devices was possible only to a restricted degree, however, since the organ dose depends not only on the detector size and the FOV but also on other factors, such as the type of detector material and the selected investigation parameters. The investigated CBCT devices with the standard settings regarding dose-related parameters (FOV, tube current time product (in milliampere-second), tube voltage (in kilovolt)) used in this study differ significantly [7, 20, 25, 29, 34]. Because of the different detector size in the CBCT devices, there are clear differences in the FOV and thus also in the dose. Depending on the positioning of the FOV, this can lead to large differences in the radiation dose of the individual radiosensitive organs in the same investigated device. A direct comparison of the organ dose determined here with previously published studies did not appear reasonable because the phantoms used in each study differed significantly in terms of the number and positioning of the TLDs as well as the settings used [7, 9, 10, 14, 25, 29, 33]. If the number of TLDs is too low, for example, the outcome of the dose measurement can be incorrect by up to 80 % [33].

MSCT radiation dose

Particularly among the low-dose MSCT devices, a comparison with the literature was not possible due to the extreme choice of parameters. Despite the fact that the FOV, tube voltage, and tube current were identical, the doses of the three MSCT devices differed due to different detector geometries and material, pre-filtering, and tube current modulation. This can be seen in the varying CTDI values [1]. A reduction of the tube current time product (in milliampere-second) and tube voltage (in kilovolt) leads to a reduction in radiation exposure. Reducing the tube current time product (in milliampere-second) by half also decreases the applied dose by 50 %, and the contrast-to-noise ratio is reduced by the square root of 2. This means that when the dose decreases and the tube current time product is reduced, noise increases disproportionally [7]. Suomalainen et al. [7] and Kyriakou et al. [20] determined that the use of low-dose protocols led to a similar high-contrast resolution with CBCT and MSCT devices at comparable organ doses.
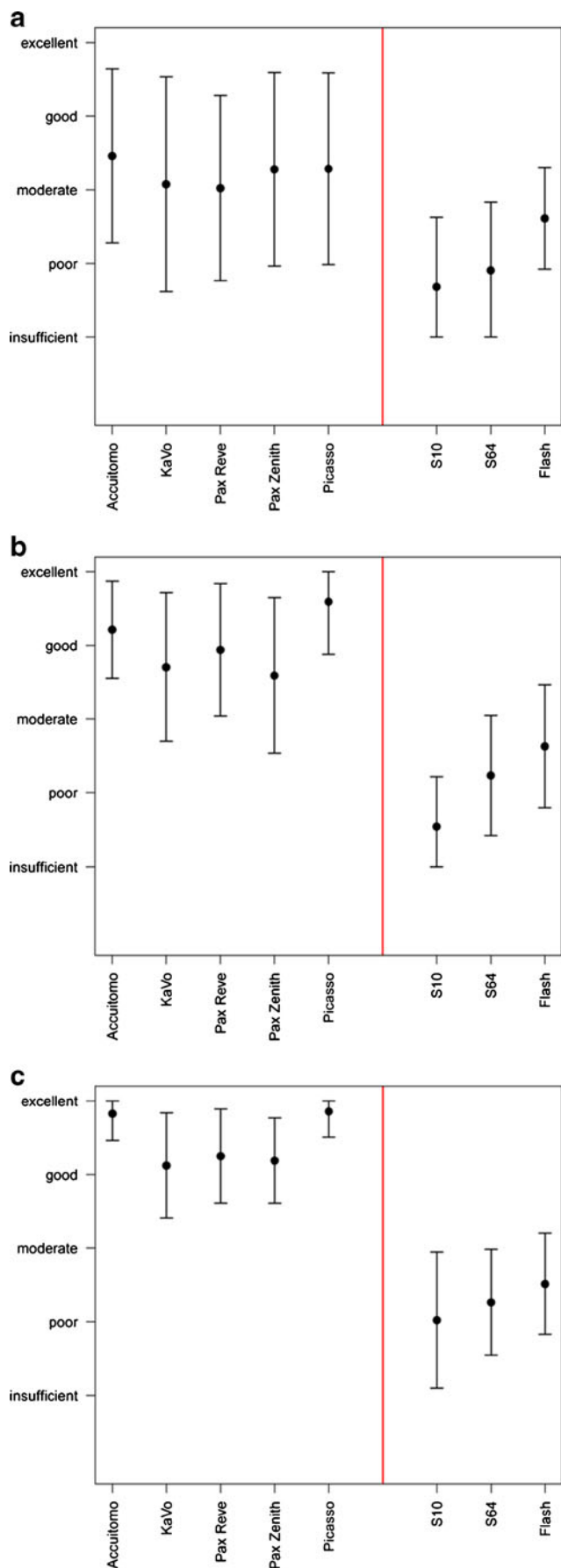
◀ **Fig. 2** Error bar plot for the enamel–dentin border (**a**), the dentin–pulpal border (**b**), and the apical third of the periodontal space (**c**) showing means (*dots*) and standard deviations (±) of the image quality ratings

CBCT–MSCT comparison

We did not believe that a consideration of the effective dose was reasonable because of the significant differences regarding the field of view specified by the manufacturer for the CBCT. Furthermore, we only used the head part of the RANDO Phantom, because our initial measurements have shown that all other organ doses are neglectable. Therefore, we can only give organ dose values. If the dose values for the individual studied radiosensitive organs are examined, significant differences with respect to the organ dose become apparent, particularly in the area of the cerebrum; these can be mainly explained by the different z-coverage of the devices tested. Due to the low coverage in the z-direction, i.e., in the area of the longitudinal body axis, only very low organ doses were measured when focusing on the dental area in the cerebrum and the cerebellum—as is the case for the eye lenses using the Picasso Trio—since only scattered radiation is involved here. The height of scan might also be the reason why for the Picasso Trio only relatively low organ doses were measured.

For the other CBCT units—which exhibited a larger scan volume in the z-direction, which resulted in parts of the brain lying directly in the beam path—markedly higher dose levels were measured in the area of the brain. The differences between the studied CBCT and MSCT devices with similar FOVs were especially striking in the area of the eye lens: Particularly for the 3D Accuitomo 170, a dose of 8.30 mSv was measured for the TLDs located in the area of the eye lenses (TLD location 3, see Table 1). Interestingly, the Pax Zenith 3D, the Pax Reve 3D, and the 3D eXam, which show a comparable height of scan, displayed enormous differences regarding the dose measured at TLD location 3 (Table 1). Whereas the dose for the eye lenses was relatively low in the Pax Reve 3D (0.54 mSv), all the other TLD doses in the Pax Reve 3D were decisively higher compared to the Pax Zenith 3D and the 3D eXam. According to the Federal Office for Radiation Protection in Germany, the dosage limit for the populace in the area of the eye lens is 15 mSv [35].

Similar results were visible for the thyroid gland. Here, the dose measured at the TLD location of the thyroid gland (TLD locations 8 and 9) was highest for the Pax Reve 3D (2.78 mSv). Devices with a similar or even higher coverage in the z-direction displayed a distinctly lower dose.

If the radiation doses for the investigated MSCT devices are examined, it becomes apparent that these are nearly identical for the SOMATOM Sensation 64 and the SOMATOM Definition Flash, whereas the SOMATOM Sensation 10 displayed

Table 7 p values of Wilcoxon–Nemenyi–McDonald–Thompson tests

		3D Accuitomo 170	SOMATOM Definition Flash	3D eXam	Pax Reve 3D	Pax Zenith 3D	Picasso Trio	SOMATOM Sensation 10
SOMATOM Definition Flash	ED	0.02*						
	DP	<0.001*						
	PS cervical	<0.001*						
	PS medial	<0.001*						
	PS apical	<0.001*						
3D eXam	ED	0.38	0.95					
	DP	0.57	0.08					
	PS cervical	0.17	0.05*					
	PS medial	0.07	0.06					
	PS apical	0.22	<0.001*					
Pax Reve 3D	ED	0.3	0.98	1				
	DP	0.99	<0.001*	0.97				
	PS cervical	0.38	0.01*	1				
	PS medial	0.81	<0.001*	0.85				
	PS apical	0.43	<0.001*	1				
Pax Zenith 3D	ED	0.98	0.28	0.93	0.88			
	DP	0.39	0.16	1	0.9			
	PS cervical	0.09	0.09	1	1			
	PS medial	0.04*	0.11	1	0.74			
	PS apical	0.35	<0.001*	1	1			
Picasso Trio	ED	0.99	0.19	0.87	0.8	1		
	DP	0.95	<0.001*	0.05	0.5	0.02*		
	PS cervical	1	<0.001*	0.32	0.6	0.19		
	PS medial	1	<0.001*	0.06	0.8	0.04*		
	PS apical	1	<0.001*	0.16	0.33	0.26		
SOMATOM Sensation 10	ED	<0.001*	<0.001*	<0.001*	<0.001*	<0.001*	<0.001*	
	DP	<0.001*	0.2	<0.001*	<0.001*	<0.001*	<0.001*	
	PS cervical	<0.001*	0.73	<0.001*	<0.001*	<0.001*	<0.001*	
	PS medial	<0.001*	0.8	<0.001*	<0.001*	<0.001*	<0.001*	
	PS apical	<0.001*	0.98	<0.001*	<0.001*	<0.001*	<0.001*	
SOMATOM Sensation 64	ED	<0.001*	0.01*	<0.001*	<0.001*	<0.001*	<0.001*	1
	DP	<0.001*	0.96	<0.001*	<0.001*	0.01*	<0.001*	0.86
	PS cervical	<0.001*	0.93	<0.001*	<0.001*	<0.001*	<0.001*	1
	PS medial	<0.001*	0.99	<0.001*	<0.001*	0.01*	<0.001*	1
	PS apical	<0.001*	1	<0.001*	<0.001*	<0.001*	<0.001*	1

All p values are adjusted for multiple comparisons

ED enamel–dentine junction, DP dentine–pulp border, PS cervical cervical third of the periodontal space, PS medial middle third of the periodontal space, PS apical apical third of the periodontal space

*$p < 0.05$ (indicates significant differences between two devices)

Table 8 Absorbed organ dose for the examined CBCT and MSCT devices (mSv)

Tissue in mSv	3D Accuitomo 170	KaVo 3D eXam	Pax Zenith 3D	Pax Reve 3D	Picasso Trio	SOMATOM Sensation 10	SOMATOM Sensation 64	SOMATOM Definition Flash
Brain (cerebrum and cerebellum)	3.30	0.57	0.43	1.13	0.13	2.00	1.12	0.80
Eye lens	8.30	1.53	2.38	0.54	0.32	2.81	1.42	1.22
Thyroid gland	0.67	0.43	1.54	2.78	0.74	2.12	0.93	0.72
Bone surface	3.41	0.16	0.13	0.48	0.03	2.00	1.09	0.88

slightly higher dose values. The higher dose values—compared to the other two MSCT devices—for the SOMATOM Sensation 10 are caused by a tube-side preliminary filter for examinations of the head in this device. In addition, this device has a smaller distance between the focus and the detector.

Metal artifacts

In the presence of metal restorations (crowns or amalgam fillings), the resulting artifacts appeared to be less pronounced in the examined CBCT devices than in the MSCT devices, corresponding to the observations of Carrafiello [16] and Pauwels [4]. According to Kyriakou et al. [20] and Schulze et al. [36], the differences in regard to the metal artifacts between the two groups of devices are due to different scanning and scatter radiation conditions. The metal artifacts within the CBCT group were represented quite homogeneously. However, there were significant differences in the artifact behavior within the MSCT group: In the SOMATOM Definition Flash, the diagnosis of adjacent structures by light and dark stripes was disturbed less than in the SOMATOM Sensation 10 and Sensation 64.

Summary and clinical conclusions

The results make it clear that CBCT systems are a very heterogeneous group of devices which differ significantly despite a largely similar FOV, resulting in a comparable range of indications in the standard settings recommended by the manufacturer. In the present study, this manifests itself especially in significant differences in the organ doses with a similar image quality. In most of the scanners used in this study, only a slight modification of the investigation parameters is possible, whereas the 3D Accuitomo 170 allows a larger individual selection of parameters.

In contrast, the MSCT technology provides the opportunity to create an optimized investigation protocol according to medical indications [10, 20]. In our study, we decided on an extremely low-dose protocol; as a result, the organ doses for the patient were in the middle of the field for CBCT devices. However, this was significantly lower than the organ dose values of the 3D Accuitomo 170, which were in the range of a normal MSCT examination protocol [5, 11]. Yet this significant reduction in the tube current time product (in milliampere-second) and tube voltage (in kilovolt) in the MSCT devices resulted in an increase in image noise and thus to a lower picture quality compared with CBCT devices. This made it more difficult to diagnose the investigated dental structures in our study. In their study, Kyriakou et al. [20] came to the conclusion that at the same or lower radiation exposure, MSCT devices can produce more homogeneous images of equivalent quality than CBCT devices. It can be seen in our study that if the tube voltage and the tube current are reduced further, the diagnosis of delicate structures is made more difficult due to a significant increase in noise. Depending on the clinical problem, however, a critical examination must be made whether the increase in image quality, which is usually associated with a higher radiation dose for the patient, is relevant to the therapy and is therefore justified. Especially in the study of system anomalies and craniofacial malformations in children using appropriate MSCT low-dose examination protocols, exposure should be reduced as much as possible.

When choosing the adequate device for creating a 3D radiographic dataset for a given patient, several others factors apart from the radiation dose, such as the availability or the costs of the generation of a 3D data set, must be taken into account. Another important factor is surely the positioning of the patient when taking a picture and the time necessary to create the image.

From the radiological point of view, the adjustment of similar scan parameters would have been reasonable for the organ dose measurement and the investigation of the image quality. Because of the heterogeneity of the investigated devices, this was not possible.

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