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ORIGINAL ARTICLE

Radiation dose of cone-beam computed tomography compared to conventional radiographs in orthodontics

Strahlenbelastung beim digitalen Volumentomogramm im Vergleich zu konventionellen kieferorthopädischen radiologischen Unterlagen

Luca Signorelli[1] · Raphael Patcas[1] · Timo Peltomäki[2] · Marc Schätzle[1]

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Abstract

Objectives The aim of this study was to determine radiation doses of different cone-beam computed tomography (CBCT) scan modes in comparison to a conventional set of orthodontic radiographs (COR) by means of phantom dosimetry.

Materials and methods Thermoluminescent dosimeter (TLD) chips (3 × 1 × 1 mm) were used on an adult male tissue-equivalent phantom to record the distribution of the absorbed radiation dose. Three different scanning modes (i.e., portrait, normal landscape, and fast scan landscape) were compared to CORs [i.e., conventional lateral (LC) and posteroanterior (PA) cephalograms and digital panoramic radiograph (OPG)].

Results The following radiation levels were measured: 131.7, 91, and 77 µSv in the portrait, normal landscape, and fast landscape modes, respectively. The overall effective dose for a COR was 35.81 µSv (PA: 8.90 µSv; OPG: 21.87 µSv; LC: 5.03 µSv).

Discussion Although one CBCT scan may replace all CORs, one set of CORs still entails 2–4 times less radiation than one CBCT. Depending on the scan mode, the radiation dose of a CBCT is about 3–6 times an OPG, 8–14 times a PA, and 15–26 times a lateral LC. Finally, in order to fully reconstruct cephalograms including the cranial base and other important structures, the CBCT portrait mode must be chosen, rendering the difference in radiation exposure even clearer (131.7 vs. 35.81 µSv). Shielding radiation-sensitive organs can reduce the effective dose considerably.

Conclusion CBCT should not be recommended for use in all orthodontic patients as a substitute for a conventional set of radiographs. In CBCT, reducing the height of the field of view and shielding the thyroid are advisable methods and must be implemented to lower the exposure dose.

Keywords Radiation dosage · Diagnostic techniques · Organs at risk · Thyroid · Phantoms, imaging

Zusammenfassung

Zielsetzung Unter Verwendung phantomdosimetrischer Methoden sollten die Strahlendosen unterschiedlicher DVT (Digitales Volumentomogramm; "cone-beam computed tomography", CBCT)-Aufnahmeprotokolle mit denen beim Erstellen kompletter konventioneller radiologischer Unterlagen verglichen werden.

Material und Methoden An einem Phantom (gewebeäquivalent einem erwachsenen Mann) wurden TLD("thermoluminescent dosimeter")-Chips (3x1x1 mm) verwendet, um die Verteilung der absorbierten Strahlendosis zu registrieren. Die Dosen bei 3 unterschiedlichen DVT-Aufnahmeprotokollen (Hochformat, normales Querformat, schnelles Querformat) wurden verglichen mit denen konventioneller kieferorthopädischer Aufnahmen [d. h. seitliches Fernröntgenbild, PA(posterior-anterior)-Aufnahme, und digitales Orthopantomogramm (OPT)].

Ergebnisse Für die Protokolle Hochformat, normales Querformat und schnelles Querformat wurden 131,7, 91 bzw. 77 µSv gemessen. Die effektive Gesamtdosis für die konventionellen kieferorthopädischen Aufnahmen lag bei

L. Signorelli: PD Dr. med. dent. & Odont Dr. MOrtho RCSEd

✉ Marc Schätzle
marc.schaetzle@zzm.uzh.ch

[1] Clinic for Orthodontics and Pediatric Dentistry, Center for Dental Medicine, University of Zurich, Plattenstrasse 11, 8032 Zurich, Switzerland

[2] Dental and Oral Diseases Outpatient Clinic, Department of Eye, Ear and Oral Diseases, Hospital and Department of Otolaryngology, Tampere University, Tampere, Finland

35,81 µSv (PA-Aufnahme: 8,90 µSv; OPT: 21,87 µSv; seitliches Fernröntgenbild: 5,03 µSv).
Diskussion Zwar lassen sich mit einem DVT sämtliche konventionellen kieferorthopädischen Röntgenunterlagen ersetzen, doch ein komplettes Set konventioneller Unterlagen bedeutet immer noch 2- bis 4-mal weniger Strahlung als ein DVT. Abhängig vom Aufnahmeprotokoll liegt die Strahlendosis beim DVT 3- bis 6-mal so hoch wie bei einem OPT, 8- bis 14-mal so hoch wie bei einer PA-Aufnahme und 15- bis 26-mal so hoch wie bei einem seitlichen Fernröntgenbild. Ferner erfordert eine vollständige kephalometrische Rekonstruktion einschließlich der Schädelbasis und anderer relevanter Strukturen beim DVT den Einsatz des Hochformats; damit wird der Unterschied in der Strahlenbelastung noch deutlicher: 131,7 vs. 35,81 µSv. Die Abschirmung strahlensensibler Organe kann die effektive Strahlendosis wesentlich reduzieren.
Schlussfolgerung Zum Einsatz für alle kieferorthopädischen Patienten statt konventioneller Röntgenunterlagen ist die DVT nicht zu empfehlen. Um die Strahlenbelastung beim DVT zu verringern, sollten die Höhe des Sichtfeldes reduziert und die Schilddrüse abgeschirmt werden.

Schlüsselwörter Strahlendosis · Diagnostische Verfahren · Gefährdete Organe · Schilddrüse · Phantome für Strahlendiagnostik

Introduction

Diagnosis and treatment planning for orthodontic patients is based on a combination of study casts, intraoral and extraoral photographs, and radiographs commonly comprising a panoramic radiograph (OPG) and lateral as well as anteroposterior cephalograms. Since the introduction of cephalometry by Broadbent and Hofrath in 1931 [10, 18], lateral and anteroposterior cephalograms have been important tools for orthodontists studying dental malocclusions and underlying skeletal discrepancies and deformities [5, 6, 9, 32]. OPG has been in use in orthodontics for the diagnosis of hyper- and hypodontia, assessment of the topography of unerupted teeth, evaluation of the developmental stages of teeth, root resorption, and overall pathologies of the jaws. Nevertheless, conventional lateral as well as anteroposterior cephalometry and OPG are limited, essentially because (1) they provide only a 2-dimensional (2D) representation of 3-dimensional (3D) structures; (2) in OPG images, significant distortion exists owing to varying amounts of horizontal and vertical magnification, and lateral cephalometry suffers from different magnification due to different distances from the film; and (3) due to the superimposition of different structures. Despite these inherent limitations, overcoming the aforementioned limitations would be beneficial.

Cone-beam computed tomography (CBCT) offers the evident advantage of representing 1:1 geometry of the true 3-dimensional (3D) morphology of the skeletal structures of the cranium, allowing accurate measurements and making simulations of surgical and orthodontic procedures possible. There is evidence that the use of CBCT allows more accurate diagnosis of skeletal asymmetry [13], easier localization of impacted and supernumerary teeth, assessment of root resorption [2, 7], improved surgical planning, and better detection of pathologies [14, 17, 20]. This improved diagnostic tool may change a given diagnosis and its subsequent treatment approach [8]. Even though there is no other X-ray technique that renders anatomic measures so reliably for quantitatively assessing buccal and lingual bone height and buccal bone thickness with high precision and accuracy [4, 28, 36], a CBCT protocol of 0.125-mm voxel might still not depict the thin buccal alveolar bone covering reliably, and there is a risk of overestimating fenestrations and dehiscences [29].

However, the cost–benefits of CBCT scanning are supposed to be superior to the combination of several 2D radiographic images with respect to the intrinsic information, and to CT in terms of the radiation dose and cost. The replacement of conventional plain radiographs with 3D-capable devices appears to be an unavoidable trend [27]. In 18 % of American and Canadian postgraduate orthodontic residency programs, CBCT is already being used as a diagnostic tool for every patient [35].

Although CBCT scans employ less radiation than computed tomography (CT) scans, CBCT scanning for every orthodontic patient has been questioned by a few practitioners [16]. In addition, many guidelines (such as those of the American Association of Orthodontics [3] or British Orthodontic Society [19]) do not recommend routine use of CBCT, even though some investigators report that a CBCT scan might expose a patient to 5–16 times the amount of radiation of a panoramic radiograph [26, 33]. More recent low-dose scan protocols may reduce the radiation exposure dramatically, yielding enough information for orthodontic diagnostics [23]. As most orthodontic patients are children, considered to be especially sensitive to ionizing radiation, all potential benefits of CBCT imaging must be weighed against potential risks [11, 24, 30, 31] and the aforementioned guidelines must—should new evidence emerge—be carefully re-evaluated.

The aim of this study was to examine the radiation doses of different CBCT scan modes in comparison to a conventional set of orthodontic radiographs (CORs) by means of phantom dosimetry.

Materials and methods

The radiological devices and their settings used in this study correspond to the clinical arrangements generally used and described in the literature [30]. Thermoluminescent dosimeter (TLD) chips (3 mm × 1 mm × 1 mm) were used on selected locations in the head and neck region of an adult male tissue-equivalent phantom (RANDO®, radiation analog dosimetry system; The Phantom Laboratory, Salem, NY, USA) to record the distribution of the absorbed radiation dose. The 19 sites appraised in this study are listed in Table 1. These locations reflect critical organs known to be sensitive to radiation. The TLD chips were supplied by the Institute of Applied Radiophysics (IAR) from the University of Lausanne, Switzerland. The exposed dosimeters were analyzed by the IAR. One unexposed dosimeter served as control for environmental radiation.

The CBCT scans were taken by the KaVo 3D eXam® (KaVo Dental GmbH, Biberach/Riß, Germany) using three different scanning modes: portrait mode (17 cm scan height, 120 kV tube voltage, 5 mA tube current, 8.9 s scan time, 3.7 s exposure time, 18.54 mAs tube current time product), normal landscape mode (reduced scan height of 13 cm, other parameters left unaltered), and fast scan landscape mode (reduced scan height of 13 cm, 5 s scan time, 2 s exposure time, other parameters left unaltered).

The assessed CORs consisted of a conventional lateral (LC) and posteroanterior (PA) cephalograms and digital panoramic radiograph (OPG). LC and PA were performed on a custom-made X-ray unit (COMET, 3175 Flamatt, Switzerland) with the following parameters for the lateral cephalogram: 67 kV tube voltage, 250 mA tube current, 0.04 s exposure time, and 10 mAs tube current time product; for PA: 67 kV tube voltage, 250 mA tube current, 0.164 s exposure time, and 40 mAs tube current time product; and for OPG: 65 kV tube voltage, 6 mA tube current, 19 s exposure time, and 114 mAs tube current time product.

Because of the relatively small amount of radiation required for a single examination, ten exposures were taken sequentially to provide more reliable data. The total measured value was then divided by ten and used for further calculations. Doses from TLDs at different positions within a tissue or organ were averaged to express the average tissue-absorbed dose in micrograys (μGy). These values were used to calculate the equivalent dose H_T using the following equation:

$$H_T = \sum W_R D_T.$$

The equivalent dose H_T for a tissue or organ is defined as the product of the radiation weighting factor W_R (W_R equals 1 for *x*-radiation) and the measured absorbed dose D_T averaged over a particular tissue or organ [37].

Effective dose E has been recommended by the International Commission on Radiological Protection (ICRP) as a means of comparing the detriment of different exposures to ionizing radiation to an equivalent detriment produced by a full-body dose of radiation. The risk to the whole body is, thus, determined as the summation of the equivalent doses established for all tissues and organs [37]. The effective dose (E_{ICRP60}), expressed in microsieverts (μSv), was calculated using the equation

$$E = \sum w_T H_T$$

where E is the product of the tissue weighting factor w_T, which represents the relative contribution of that organ or tissue to the overall risk, and the equivalent dose H_T. The weighting factors of the equivalent doses in accordance with the ICRP guidelines of 2007 are listed in Table 2.

Results

The obtained absorbed doses, equivalent doses, and effective doses are given in Tables 3, 4 for the different CBCT scan modes. For the CORs, these values

Tab. 1 Thermoluminescent dosimeter (TLD) chip locations on the RANDO® phantom
Tab. 1 Lokalisierungen der thermolumiszenten Dosimeter (*TLD*) im RANDO®-Phantom

Organ	Location	TLD number	Phantom level
Brain	Anterior/posterior	18, 19	1
	Right/left	16, 17	2
	Hypophysis	13	3
Eyes	Right/left lens	14, 15	3
Skull	Maxillary sinus right/left	9, 10	5
Salivary glands	Right/left parotid	11, 12	5
	Right/left submandibular gland	7, 8	6
	Sublingual gland	5	
Thyroid	Right/left	1, 2	9
Spine	B2	6	6
	Right/left	3, 4	7

Tab. 2 Weighting of equivalent dose (H_T) for head radiation exposure
Tab. 2 Gewichtung der Äquivalenzdosen (H_T) für die Strahlenbelastung des Kopfes

Tissue	ICRP identified organ	Fraction of total organ irradiated (%)	Corresponding TLD numbers	Fraction irradiated (%)	Weighting	Weighting in (%)
Bone marrow				16.5	1.98	17.86
	Mandibula	1.30	Mean 7, 8			
	Calvarium	11.80	Mean 16, 17, 18, 19			
	Cervical spine	3.40	Mean 3, 4, 6			
Esophagus	Esophagus	10.00	Mean 1, 2	10.0	4.00	36.08
Thyroid	Thyroid	100.00	Mean 1, 2	100.0	0.40	3.61
Bone surface				16.5	0.77	6.91
	Mandible	1.30	4.64 × mean 7, 8			
	Calvarium	11.80	4.64 × mean 16, 17, 18, 19			
	Cervical spine	3.40	4.64 × mean 3, 4, 6			
Brain	Brain	100.00	Mean 13, 16, 17, 18, 19	100.0	1.00	9.02
Salivary glands				100.0	0.05	0.45
	Parotis	33.00	Mean 11, 12			
	Submandibular	33.00	Mean 7, 8			
	Sublingual	33.00	5			
Skin	Skin	5.0	Mean 11, 12, 14, 15	5.0	1.00	9.02
Muscle	Muscle	5.0	Mean 1–8, 11–13	5.0	0.05	0.41
Remainder					1.85	16.64
	Lymphatic nodes	5.0	Mean 1–8, 11–12			
	Extra thoracic airway	100.00	Mean 1–8, 11–14			
	Oral mucosa	100.00	Mean 1–8, 11–15			

TLD thermoluminescent dosimeter, *ICRP* International Commission on Radiological Protection

Tab. 3 Equivalent dose (µSv) for the different CBCT exposure protocols
Tab. 3 Äquivalenzdosen (µSv) für die verschiedenen DVT-Aufnahmeprotokolle

	Bone marrow	Thyroid	Esophagus	Bone surface	Salivary glands	Skin	Brain	Remainder
Portrait mode	189.08	1090.00	109.00	877.33	1466.52	64.75	1020.00	2971.20
Normal landscape scan mode	123.32	306.00	30.60	572.19	1926.47	92.50	502.40	3532.46
Fast landscape scan mode	120.03	233.00	23.30	556.96	1522.51	63.40	503.60	2894.42

Tab. 4 Effective dose (µSv) for the different CBCT exposure protocols
Tab. 4 Effektive Dosen (µSv) für die verschiedenen DVT-Aufnahmeprotokolle

	Bone marrow	Thyroid	Esophagus	Bone surface	Salivary glands	Skin	Brain	Remainder	Total
Portrait mode	22.69	43.60	4.36	8.77	14.67	0.65	10.20	26.74	131.68
Normal landscape scan mode	14.80	12.24	1.22	5.72	19.26	0.93	5.02	31.79	90.99
Fast landscape scan mode	14.40	9.32	0.93	5.57	15.23	0.63	5.04	26.05	77.17

are listed in Tables 5, 6. The large portrait mode caused high radiation exposure with 131.7 µSv; in the smaller normal landscape mode, we observed a noticeable reduction in radiation exposure to 91 µSv and a further reduction in the fast landscape mode (77.2 µSv).

Tab. 5 Equivalent dose (µSv) for COR: OPG, LC and AP cephalogram
Tab. 5 Äquivalenzdosen (µSv) für die konventionellen kieferorthopädischen radiologischen Unterlagen, seitliches Fernröntgenbild, PA-Aufnahme und OPT

	Bone marrow	Thyroid	Esophagus	Bone surface	Salivary glands	Skin	Brain	Remainder
COR	41.51	104.50	10.45	192.59	818.25	32.51	127.00	1613.67
LC	6.01	45.00	4.50	27.87	59.99	2.88	30.00	124.54
PA	20.71	20.00	2.00	96.11	126.65	4.75	92.00	260.41
OPG	14.79	39.50	3.95	68.61	631.60	24.89	5.00	1228.72

COR conventional orthodontic radiographs, *OPG* digital panoramic radiograph, *LC* lateral cephalogram, *AP* anteroposterior cephalogram

Tab. 6 Effective dose (µSv) for COR: OPG, LG and AP cephalogram
Tab. 6 Effektive Dosen (µSv) für konventionelle kieferorthopädische radiologische Unterlagen, seitliches Fernröntgenbild, PA-Aufnahme und OPT

	Bone marrow	Thyroid	Esophagus	Bone surface	Salivary glands	Skin	Brain	Remainder	Total
COR	4.98	4.18	0.42	1.93	8.18	0.33	1.27	14.52	35.81
LC	0.72	1.80	0.18	0.28	0.60	0.03	0.30	1.12	5.03
PA	1.98	4.00	0.40	0.77	1.00	0.05	1.00	1.89	11.09
OPG	1.77	1.58	0.16	0.69	6.32	0.25	0.05	11.06	21.87

COR conventional orthodontic radiographs, *OPG* digital panoramic radiograph, *LC* lateral cephalogram, *AP* anteroposterior cephalogram

The overall effective dose for a COR was 35.81 µSv (PA: 8.90 µSv; OPG: 21.87 µSv; LC: 5.03 µSv). Although just one CBCT scan may replace all the CORs, one set of CORs still entailed 2–4 times less radiation than one CBCT. Depending on the scan mode, the radiation dose of a CBCT was about 3–6 times an OPG, 8–14 times a PA, and 15–26 times a lateral LC. It should be noted that the radiation dose depends on the type of CBCT device and could thus be reduced even further.

It is obvious, however, that to fully reconstruct cephalograms including the cranial base and other important referential structure, a CBCT portrait mode must be chosen, rendering the difference in radiation exposure even clearer (131.7 vs 35.81 µSv). It is important to consider that the thyroid is the most vulnerable organ, followed by the salivary glands (Tables 3, 4, 5, 6). Thus, the use of a thyroid shield in the CBCT considerably reduces the effective dose. In theory, complete shielding of the thyroid from radiation exposure would decrease the total effective dose from 131.7 to 96.24 µSv for the portrait mode, from 90.99 to 77.74 µSv for the normal landscape scan mode, and from 77.17 to 67.85 µSv for the fast landscape scan mode, respectively. This would represent a dose reduction of 12–27 %. Thus, a portrait mode scan (17 cm FOV) with a thyroid shield would probably incur only a little more radiation exposure than a smaller landscape mode scan (13 cm FOV) without a thyroid shield.

Discussion

Replacing conventional plain radiographs with 3D-capable devices is considered by many to be an unavoidable trend [27] because a single scan enables us to obtain the data usually acquired via different radiographs (OPG, PA, LC, [22]).

However, the results of our study suggest that the potential benefit of 3D-capable devices must be questioned because of the additional radiation associated with them, as most orthodontic patients are actively growing children who, being smaller, absorb higher doses when given the same exposure at unaltered FOV [1]. The selection criteria for an image at any treatment phase should follow the as-low-as-reasonably-achievable (ALARA) principle. The choice of CBCT should correspond to the patient's needs. A patient may only qualify for CBCT scanning if the expected additional information provided will have an impact on his or her treatment modalities or outcome. Although a single CBCT scan may be able to take the place of all the CORs, our study shows that one set of CORs still involves 2–4 times less radiation than one CBCT. Hence, our results support the statement of the British Orthodontic Society [19] and American Association of Orthodontics [3] that CBCT should not be used routinely on every patient. This has already been confirmed by a study comparing radiation doses for conventional panoramic and cephalometric imaging with the doses for two different CBCT units and a multislice CT unit in an orthodontic practice [34]. They demonstrated that the effective radiation dose of a set of conventional PA and LC is about 5–6 times lower than the corresponding CBCT scan in their study. Their effective exposure dose for PA and LC was similar to our findings' dose (Tables 5, 6).

This risk and benefit assessment is exceedingly challenging. First, as mentioned above, only very recent new evidence of the potential harm of dental and craniofacial X-rays has been forthcoming [11, 31]. Children's exposure to X-rays during the orthodontic radiographic protocol may cause DNA damage that is still lower than the threshold value required for carcinogenesis. Despite the importance of radiographs in orthodontic treatment, no set of radiographs—neither conventional, nor a CBCT scan—is a risk-free procedure; other radiographs needed during or at the end of treatment should be taken only when necessary, as the risk–benefit relationship must always be considered [24]. In their well-received paper, Cohen calls attention to the fact that there are two risks from radiation: (1) the increased incidence of cancer and radiation exposure, and (2) the little-discussed risk of missing diagnostic data because of suboptimal image quality due to inappropriately low radiation settings [12]. Cohen even argues that "for an individual patient, the consequences of missing an abnormality because radiation exposure is too low are significantly greater than the statistical long-term risk of cancer from radiation exposure that is too high". Cohen's message is a simple call to maintain a balanced perspective between the two risks.

Second, the potential benefits of CBCT are still being debated [16, 21, 23]. The task to reduce the ionizing risk of medical radiation is one of the dentist's primary obligations and responsibilities, especially when an imaging method's efficacy is not fully understood.

Dosimetry assessment of CBCT devices on phantoms has been addressed in many studies, but the implication of the thyroid shield has not been evaluated in a comparative study. The thyroid is an organ that is highly sensitive to radiation exposure. Our study suggests that a thyroid shield reduces the effective dose remarkably well for imaging procedures involving that gland. Apparently, a relevant dose-exposure reduction is achievable for the portrait mode CBCT scan, CBCT with small field of view, and LC, but probably no significant dose reduction is attainable by applying a neck shield in an OPG and PA, as our results reveal that the thyroid gland is not very much exposed in those radiograms anyway. Further comparative studies are, however, needed to back up this observation.

A possible limitation of our study is that we only investigated one CBCT device and different radiographic equipment may generate slightly different results. But by comparing our results to data from comparable dosimetry studies of several CBCT devices, we conclude that the device we investigated operates within the same range as other large and medium field-of-view devices [15, 25, 34]. One further point ought to be addressed. We mentioned earlier that the CBCT doses applied in this study correspond to scan parameters administered routinely and to the doses prescribed by the CBCT manufacturer. Nevertheless, it is probably possible to reduce considerably the effective dose without sacrificing diagnostic information. Hence, the scan parameters the manufacturers recommend might not concur with the ALARA principle. The impact of dose reduction on diagnostic efficacy is, however, beyond the scope of this study. Furthermore, the LC and PA images for this study were acquired via analogue radiographs and not by using more modern digital imaging techniques, which may have generated less radiation. The use of digital LC and PA might even reduce the effective dose of CORs and would only enlarge the discrepancy between CORs and a CBCT scan, while the use of an analogue OPG would reduce this discrepancy.

Conclusion

This study demonstrates that, according to the overriding as low as reasonably achievable principle, CBCT should not be recommended for use in all orthodontic patients as a substitute for a conventional set of radiographs. In CBCT, reducing the height of the field of view and shielding the thyroid are advisable methods and must be implemented to lower the exposure dose.

Compliance with ethical guidelines

Conflict of interest All the authors have no conflict of interest. The accompanying manuscript does not include studies on humans or animals.

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