

## Effective dose from cone beam CT examinations in dentistry

<sup>1</sup>J A ROBERTS, MSc, <sup>2</sup>N A DRAGE, BDS, FDS, DRRRCR, <sup>3</sup>J DAVIES, BDS, MFDS, RCS(Ed) and <sup>1</sup>D W THOMAS, MSc

<sup>1</sup>Department of Medical Physics, Velindre Cancer Centre, Velindre NHS Trust, <sup>2</sup>Department of Dental Radiology, University Dental Hospital, Cardiff and Vale NHS Trust, Cardiff and <sup>3</sup>Department of Dental Radiological Imaging, Guy's Hospital, Guy's Tower, London, UK

**ABSTRACT.** Cone beam CT (CBCT) is becoming an increasingly utilized imaging modality for dental examinations in the UK. Previous studies have presented little information on patient dose for the range of fields of view (FOVs) that can be utilized. The purpose of the study was therefore to calculate the effective dose delivered to the patient during a selection of CBCT examinations performed in dentistry. In particular, the i-CAT CBCT scanner was investigated for several imaging protocols commonly used in clinical practice. A Rando phantom containing thermoluminescent dosimeters was scanned. Using both the 1990 and recently approved 2007 International Commission on Radiological Protection recommended tissue weighting factors, effective doses were calculated. The doses ( $E_{1990}$ ,  $E_{2007}$ ) were: full FOV head (92.8  $\mu$ Sv, 206.2  $\mu$ Sv); 13 cm scan of the jaws (39.5  $\mu$ Sv, 133.9  $\mu$ Sv); 6 cm high-resolution mandible (47.2  $\mu$ Sv, 188.5  $\mu$ Sv); 6 cm high-resolution maxilla (18.5  $\mu$ Sv, 93.3  $\mu$ Sv); 6 cm standard mandible (23.9  $\mu$ Sv, 96.2  $\mu$ Sv); and 6 cm standard maxilla (9.7  $\mu$ Sv, 58.9  $\mu$ Sv). The doses from CBCT are low compared with conventional CT but significantly higher than conventional dental radiography techniques.

Received 21 November 2007  
Revised 8 January 2008  
Accepted 28 January 2008

DOI: 10.1259/bjr/31419627

© 2009 The British Institute of Radiology

Cone beam CT (CBCT) produces three-dimensional information on the facial skeleton and teeth and is increasingly being used in many of the dental specialties, including orthodontics, orthognathic surgery, trauma and implantology [1–11]. The doses from CBCT are significantly lower than conventional CT, yet are higher than doses from the traditional views used in dentistry [12, 13]. Therefore, a risk/benefit analysis must be carried out before a CBCT investigation is requested. In order to assess the risk, the effective dose must first be calculated. Although several authors have published work calculating the doses from CBCT, none has studied a full range of imaging protocols that may be used in dentistry [12–15]. The International Commission on Radiological Protection (ICRP) recently published modified tissue weighting factors for the calculation of the effective dose [16] to replace those published in 1991 [17]. The most relevant difference between these factors for this study manifests itself in the inclusion of the salivary glands as an individually weighted tissue and the addition of the oral mucosa to the remainder organs, both of which were not included at all in the previous recommendations. The weighting factor of the remainder organs has increased from 0.05 to 0.12. The aim of this study was therefore to calculate the effective dose to patients (using the current and previous ICRP factors) undergoing a CBCT examination using the i-CAT scanner (Imaging Sciences International, Hatfield, PA) for those programs that may be used for all aspects of dental work. Effective doses were compared with those reported for conventional techniques commonly used in dentistry.

### Methods and materials

Images for the study were acquired using the i-CAT cone beam dental CT scanner consisting of a standard high-frequency fixed anode X-ray tube (120 kVp, 3–8 mA) and 20 × 25 cm amorphous silicon (a-Si) flat panel detector. The performance of the X-ray tube and generator were evaluated prior to the study to ensure compliance with recommended test tolerances (Institute of Physics and Engineering in Medicine Report 91 [18]). The performance of the digital detector was also assessed and compared with those results obtained at commissioning. All results were satisfactory.

All dose measurements for the study were performed using thermoluminescent dosimeter (TLD)-100 (LiF: Mg, Ti) chips, calibrated for use in CT beam conditions (120 kV, 9.95 mmAl). Calibration chips were subject to a dose of sufficient magnitude to reflect the anticipated mean TLD dose for the study. As is standard practice in radiation dosimetry, calibration was performed against an ionization chamber with calibration traceable to national standards. The chips were read using a calibrated hot gas reader.

Three chips were positioned at each of 24 locations within the head and neck region of an adult tissue-equivalent anthropomorphic Rando phantom (Figure 1). 10 additional chips were kept outside the scanning room to allow a later determination and subtraction of the mean accumulated dose due to background radiation.

To enable calculation of effective dose (in microsieverts ( $\mu$ Sv)), each site was made as close as possible to the critical organs, as described by Ludlow et al [13]. This study was selected for its robust methodology and is one of the few to consider effective dose calculation using the newly revised tissue weighting factors (discussed

Address correspondence to: J A Roberts, Department of Medical Physics, Velindre Cancer Centre, Velindre NHS Trust, Cardiff, UK. E-mail: James.Roberts@velindre-tr.wales.nhs.uk



**Figure 1.** Head/neck region of an adult Rando phantom. Numbered slices indicate the levels containing thermoluminescent dosimeters.

below). Each TLD location and identification number is displayed in Table 1, together with the phantom level. All unoccupied cavities within the phantom were plugged with tissue-equivalent rods.

Each of the 24 locations reflect the most radiosensitive organs in the head and neck region, and would therefore contribute most to the effective dose depending upon the fraction of that organ irradiated in the scan. The fractions adopted for this study were based on those used by Ludlow et al [13], which estimate the percentage of a tissue/organ exposed by a full field of view (FOV) examination (Table 2). These fractional values were then used as a baseline to derive values for each of the smaller investigated FOVs. Those organs lying outside of the

**Table 1.** Locations of thermoluminescent dosimeter chips as utilized by Ludlow et al [13] to determine effective dose

TLD ID	Phantom location	Rando level
1	Calvarium anterior	2
2	Calvarium left	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 <sup>a</sup>	3
9	Left lens of eye <sup>a</sup>	3
10	Right cheek <sup>a</sup>	5
11	Right parotid	6
12	Left parotid	6
13	Right ramus	6
14	Left ramus	6
15	Centre cervical spine	6
16	Left back of neck <sup>a</sup>	7
17	Right mandible body	7
18	Left mandible body	7
19	Right submandibular gland	7
20	Left submandibular gland	7
21	Centre sublingual gland	7
22	Midline thyroid	9
23	Left thyroid surface <sup>a</sup>	9
24	Oesophagus	9

<sup>a</sup>Thermoluminescent dosimeter positioned on the phantom surface

primary beam, but still receiving a significant dose (above background level) owing to scattered radiation, were weighted at 100% in order to avoid underestimation of the effective dose. It was appreciated that other organs in the body were unlikely to receive zero dose; however, it was felt that this would have negligible contribution to the effective dose. As performed by Ludlow et al [13], bone surface dose was calculated by multiplying the bone marrow dose for each TLD location by the ratio of the mass absorption coefficients using a factor of 4.64. Because of its late addition as a remainder organ to the ICRP 2007 tissue weighting scheme, the oral mucosa dose was taken to be indicated by the submandibular gland dose for each scan. As the submandibular gland was out of the FOV for the maxilla scans, the mean full FOV value was used. A conservative estimate of 100% irradiation of the oral mucosa was made for all scans.

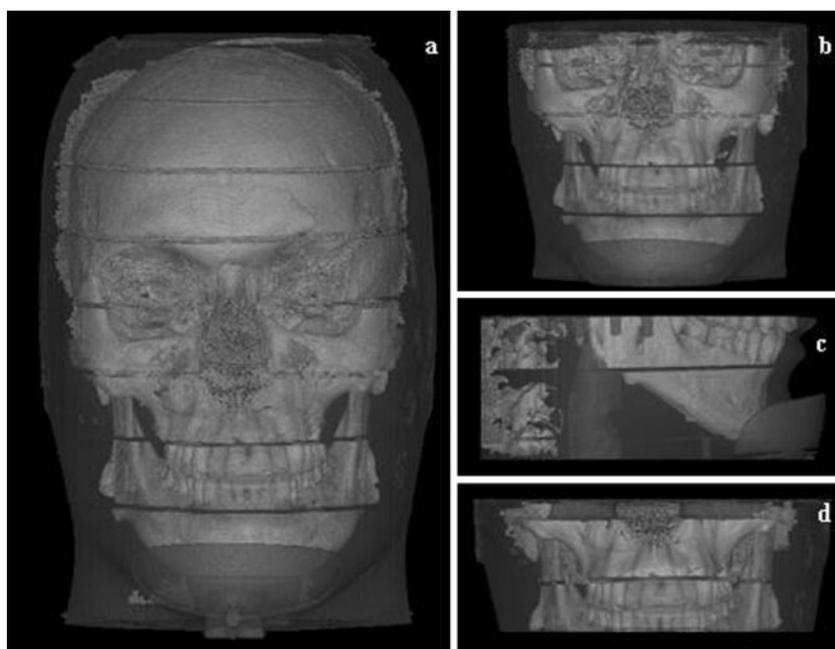
The effective dose was calculated for six commonly utilized scan volumes in dentistry: (i) full FOV head, (ii) 6 cm standard resolution mandible, (iii) 6 cm standard resolution maxilla, (iv) 6 cm high-resolution mandible, (v) 6 cm high-resolution maxilla and (vi) 13 cm scan of both jaws using both the 1990 ICRP tissue weights [17] and those recently approved (2007) by the ICRP [16] to supersede the previous factors (Table 3). Before loading the phantom with dosimeters, a scout image was acquired to verify the correct positioning within the scanner. The calculated effective dose would therefore not include the dose from this initial projection image. Figure 2 demonstrates the irradiated volumes.

In order to reduce random variation and to record a dose above the minimum reliable detection level, each scan was performed 10 times. The mean dose recorded by 3 dosimeters at each of the 24 sites was used to calculate the radiation weighted dose ( $H_T$ ) given by the product of the background subtracted mean organ TLD dose and the fraction of that tissue/organ in the irradiated field. The effective dose  $E$  (expressed in  $\mu\text{Sv}$ ) was calculated as the product of the radiation weighted dose and the relevant ICRP tissue weighting factor ( $w_T$ ) summed over all of the tissues/organs exposed (*i.e.*  $E = \sum w_T \times H_T$ ). The tissue weighting factor represents the relative radiosensitivities of the organs, and therefore the contribution of that organ to the overall risk. The effective dose  $E$  allows the risk to the whole body to be expressed, thereby giving a broad indication of the level of detriment to health from the exposure.

In order to test reproducibility of the procedure, the full FOV examination was performed on two separate occasions. This would enable assessment of the difference in calculated effective dose owing to variations in set-up, *i.e.* caused by small changes in individual chip positions within the phantom cavities and phantom alignment within the scanner.

## Results

The maximum deviation from the mean dose was calculated for each site. For all scan protocols investigated, an average of 5% variation was recorded overall. A high level of reproducibility was achieved between repeated full FOV scans performed on separate occa-



**Figure 2.** Three-dimensional reconstructions of the irradiated regions: (a) full field of view head; (b) 13 cm scan of the jaws; (c) 6 cm mandible; and (d) 6 cm maxilla.

sions. The mean effective dose was calculated as 92.8  $\mu$ Sv and 206.2  $\mu$ Sv, with a percentage range of variation between the repeats of 4.8% and 2.7% for the ICRP 1990 and ICRP 2007 weighting factors, respectively. Figure 3 displays the calculated effective dose ( $\mu$ Sv) for the full range of examinations possible with CBCT. The results obtained by Ludlow et al [13] for the full field of view examination calculated using only the 1990 weighting

factors are included. The final 2007 tissue weighting factors were not available to Ludlow et al [13] at the time of publication, only the 2005 draft.

Comparison of effective dose, calculated as a multiple of the full FOV scan for each of the smaller scan volumes, can be seen in Table 4. The dose as a percentage of annual background radiation dose in the UK [19] is also displayed.

**Table 2.** Estimated fraction of organ irradiation and the dosimeters used to provide an indication of dose to each organ

	Fraction irradiated (%)				TLD ID (from Table 1)
	Full FOV <sup>a</sup>	6 cm mandible	6 cm maxilla	13 cm mandible/maxilla	
<b>Bone marrow</b>	16.5	5.0	5.0	10.0	
Mandible	1.3	1.3	0.7	1.3	13, 14, 17, 18
Calvaria	11.8	2.0	2.6	5.3	1, 2, 3
Cervical spine	3.4	1.7	1.7	3.4	15
<b>Thyroid</b>	100.0	100.0	100.0	100.0	22, 23
<b>Oesophagus</b>	10.0	10.0	7.0	10.0	24
<b>Skin</b>	5.0	2.0	2.0	4.0	8, 9, 10, 16
<b>Bone surface</b>	16.5	5.0	5.0	10.0	
Mandible	1.3	1.3	0.7	1.3	13, 14, 17, 18
Calvaria	11.8	2.0	2.6	5.3	1, 2, 3
Cervical Spine	3.4	1.7	1.7	3.4	15
<b>Salivary glands</b>	100.0	100.0	100.0	100.0	
Parotid	100.0	100.0	100.0	100.0	11, 12
Submandibular	100.0	100.0	100.0	100.0	19, 20
Sublingual	100.0	100.0	100.0	100.0	21
<b>Brain</b>	100.0	20.0	40.0	60.0	4, 5
<b>Remainder</b>					
Brain	100.0	20.0	40.0	60.0	4, 5
Lymphatic nodes	5.0	5.0	5.0	5.0	11, 12, 19, 20, 23
Muscle	5.0	5.0	5.0	5.0	6, 7, 15, 21, 24
Extrathoracic tissue	100.0	100.0	100.0	100.0	11, 12, 19, 20, 21
Oral mucosa	100.0	100.0	100.0	100.0	19, 20 <sup>b</sup>
<b>Pituitary</b>	100.0	100.0	100.0	100.0	5
<b>Eyes</b>	100.0	100.0	100.0	100.0	6, 7, 8, 9

FOV, field of view; TLD, thermoluminescent dosimeter.

<sup>a</sup>Values derived by Ludlow et al.

<sup>b</sup>Submandibular gland dose used to indicate oral mucosa dose.

**Table 3.** 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
Oesophagus	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	Rem	0.01
Salivary glands	n/a	0.01
Skin	0.01	0.01
Remainder tissues <sup>a</sup>	0.05	0.12

Rem, remainder organ; n/a, not applicable.

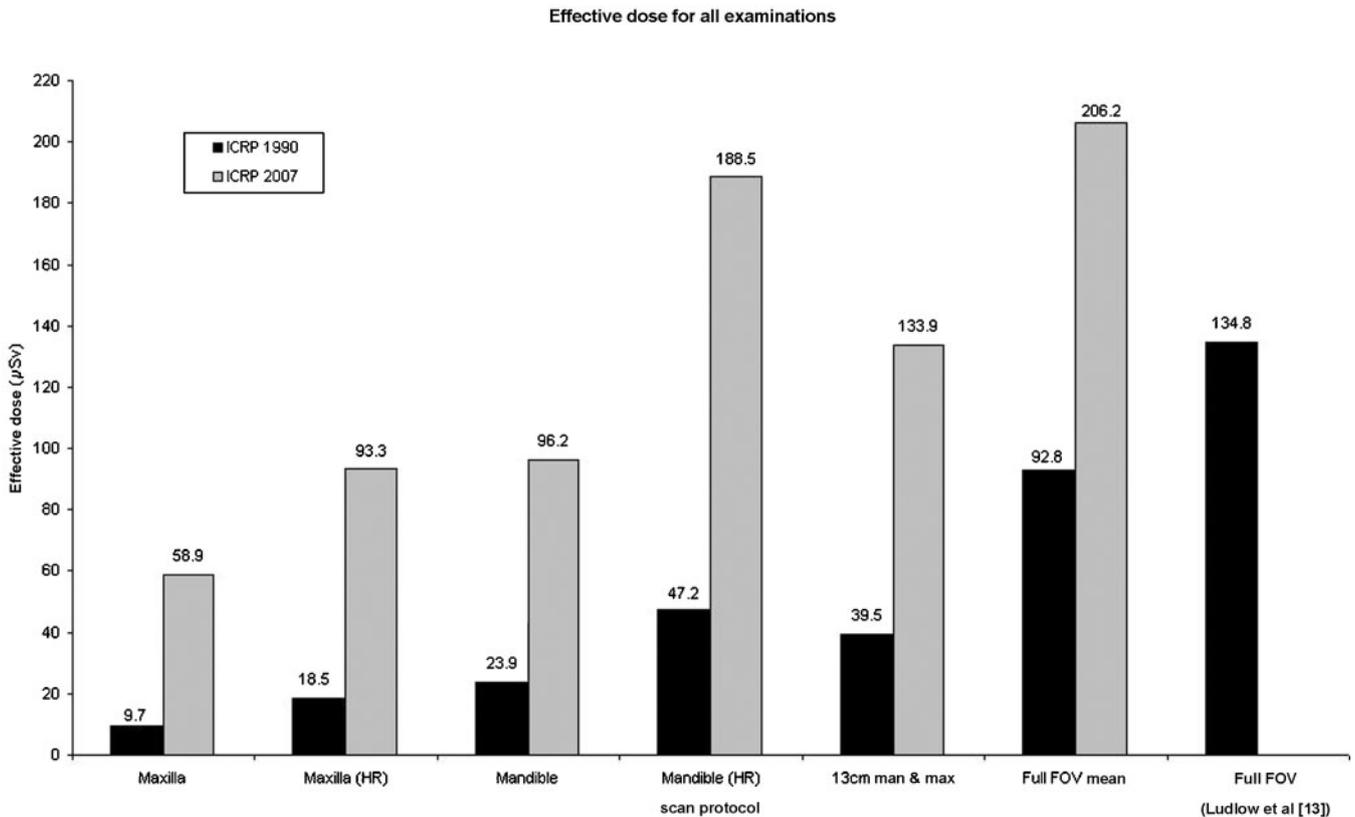
<sup>a</sup>1990 — adrenals, brain, upper large intestine, small intestine, kidney, muscle, pancreas, spleen, thymus, uterus. 2007 — adrenals, extrathoracic airways, gall bladder, heart, kidneys, lymphatic nodes, muscle, oral mucosa, pancreas, prostate, small intestine wall, spleen, thymus, uterus/cervix.

Table 4 displays the calculated effective doses for each scan technique using both ICRP 1990 and 2007 tissue weighting factors.

### Discussion

The effect of the change in ICRP tissue weighting factors for examinations of the head is significant (Figure 3). For the full FOV examination in which the salivary glands are fully irradiated by the primary beam, the dose using the 2007 factors is roughly double that using the 1991 factors. This is consistent with the findings of other authors who have reported a difference of a factor of two for examinations involving the head [20], e.g. dental orthopantomographic examinations.

The effective dose for a full FOV scan was found to be in good agreement with previous studies for the i-CAT scanner using the 1990 ICRP tissue weighting scheme [13]. It is therefore likely that good agreement would also have been observed between the effective doses calculated using the 2007 ICRP data. The full FOV scan may be used for imaging craniofacial abnormalities that affect the skull vault. CBCT may be used in orthognathic planning [4–7] and the 13 cm scan is used locally when three-dimensional orthognathic planning is to be carried out, as it shows the whole of the mandible and maxilla. This scan may also be used in the assessment of severe maxillofacial trauma. CBCT is advocated for the assessment of the jaws prior to implant placement [1]. The 6 cm standard resolution scans of the mandible or maxilla are ideal to assess the bony morphology in these cases. All of the above scans use standard resolution with a voxel size of 0.4 mm. CBCT may also be used to image dental anomalies and in the assessment of impacted teeth [8, 9, 21]. If the teeth are to be imaged, a higher



**Figure 3.** Effective dose (µSv) for all scan protocols. Results obtained by Ludlow et al [13] are also displayed for comparison (full field of view (FOV)). HR, high resolution.

**Table 4.** i-CAT effective dose as a result of varying techniques used in dentistry and as a percentage of the average natural background dose received in the UK each year [19]

Technique	Effective dose ( $\mu\text{Sv}$ )		Dose as multiple of full FOV		Dose as % of annual background dose in UK	
	ICRP <sub>1990</sub>	ICRP <sub>2007</sub>	ICRP <sub>1990</sub>	ICRP <sub>2007</sub>	ICRP <sub>1990</sub>	ICRP <sub>2007</sub>
Full FOV <sup>a</sup>	92.8	182.1	–	–	4.2	8.3
6 cm mandible	23.9	75.3	0.3	0.4	1.1	3.4
6 cm maxilla	9.7	36.5	0.1	0.2	0.4	1.7
6 cm mandible (HR)	47.2	148.5	0.5	0.8	2.1	6.8
6 cm maxilla (HR)	18.5	68.3	0.2	0.4	0.8	3.1
13 cm mandible and maxilla	39.5	110.5	0.4	0.6	1.8	5.0

HR, high resolution; FOV, field of view; ICRP, International Commission on Radiological Protection.

<sup>a</sup>Mean calculated effective dose.

resolution scan is generally carried out at our centre using a scanning protocol utilizing a voxel size of 0.2 mm. The effective dose was found to double for high-resolution scans. This is a direct result of twice the number of projections being performed. For a standard resolution scan, 306 separate exposures are made during the rotation, producing 306 projections that are used to construct the three-dimensional dataset. For the high-resolution scan, 599 separate exposures are made.

In contrast to other studies, three dosimeters were positioned at each of the 24 sites in/around the phantom and 10 scans were performed. This would provide more reliable and consistent data, which was demonstrated in the results by a high level of reproducibility and a low variation in recorded dose between each set of three dosimeters. The dose calculation method used by Ludlow et al [13] was modified to accommodate the non-full FOV examinations by adjusting the fraction-irradiated values. For this reason, lower fractions for some of the tissues only partially irradiated by the primary beam were adopted. However, it was ensured that the modified fractions assigned to these tissues would still provide a conservative estimate of the contribution to the effective dose.

Large and small volume cone beam scanners are commercially available. The i-CAT can be considered to be a large volume scanner, as it is able to image most of the maxillofacial skeleton. Other authors have reported doses from large volume CBCT scanners of between 50  $\mu\text{Sv}$  and 1024  $\mu\text{Sv}$ . This large spread in reported dose is mainly caused by differences in scanner models, imaging protocols and calculation techniques [12, 13, 15, 22]. With the exception of the Mercuray CBCT scanner, the doses are significantly lower than conventional CT previously reported at 2000  $\mu\text{Sv}$  for routine head examinations [23].

It is useful to compare the doses to those published for conventional films used in dentistry. The following values are based on the 1990 ICRP tissue weighting factors. The effective dose from panoramic radiography is  $\sim 13 \mu\text{Sv}$  [12], cephalometric radiography 1–3  $\mu\text{Sv}$  [24], periapical radiography 1–8  $\mu\text{Sv}$  [25] and occlusal radiography 8  $\mu\text{Sv}$  [25]. Our study therefore indicates that the i-CAT CBCT delivers a higher dose to the patient than a typical panoramic radiograph by a factor of 5–16.

The ICRP suggest a nominal probability coefficient for all radiation-induced fatal cancers averaged over the whole population to be 5% per Sievert [16]. Therefore,

the risk of fatal malignancy from a CBCT of the jaws is between 1 in 100 000 and 1 in 350 000. This risk is based on an adult patient. In orthodontics, many of the patients are children and the risk is higher. The risk to a paediatric patient is approximately twice that of an adult patient [26]. Therefore, these examinations must be fully justified before they are performed, and it is hoped that evidence-based selection criteria will be produced soon to aid the clinician in requesting these examinations.

## Conclusions

Despite CBCT doses being an order of magnitude or more below doses from conventional CT, they are still significantly higher than those from conventional dental radiography. The potential benefits of CBCT in dentistry are undisputed; however, it is imperative that their use be fully justified over conventional techniques before they are carried out.

## Acknowledgments

The authors are grateful to staff at the Radiation Protection Service Cardiff and the University Dental Hospital Cardiff for allowing use of their facilities for the research.

## References

- Guerrero ME, Jacobs R, Loubele M, Schutyser F, Suetens P, van Steenberghe D, et al. State-of-the-art on cone beam CT imaging for preoperative planning of implant placement. *Clin Oral Investig* 2006;10:1–7.
- Heiland M, Schulze D, Rother U, Schmelzle R, Heiland M, Schulze D, et al. Postoperative imaging of zygomaticomaxillary complex fractures using digital volume tomography. *J Oral Maxillofac Surg* 2004;62:1387–91.
- Ziegler CM, Woertche R, Brief J, Hassfeld S, Ziegler CM, Woertche R, et al. Clinical indications for digital volume tomography in oral and maxillofacial surgery. *Dentomaxillofac Radiol* 2002;31:126–30.
- Cevidan LH, et al. Superimposition of 3D cone-beam CT models of orthognathic surgery patients. *Dentomaxillofac Radiol* 2005;34:369–75.
- Cevidan LH, et al. Three-dimensional cone-beam computed tomography for assessment of mandibular changes after orthognathic surgery. *Am J Orthod Dentofacial Orthop* 2007;131:44–50.

6. Cevidanes LH, Franco AA, Gerig G, Proffit WR, Slice DE, Enlow DH, et al. Comparison of relative mandibular growth vectors with high-resolution 3-dimensional imaging. *Am J Orthod Dentofacial Orthop* 2005;128:27–34.
7. Holberg C, Steinhäuser S, Geis P, Rudzki-Janson I. Cone-beam computed tomography in orthodontics: benefits and limitations. *J Orofac Orthop* 2005;66:434–44.
8. Kau CH, Richmond S, Palomo JM, Hans MG. Three-dimensional cone beam computerized tomography in orthodontics. *J Orthod* 2005;32:282–93.
9. Mah J, Enciso R, Jorgensen M. Management of impacted cuspids using 3-D volumetric imaging. *J Calif Dent Assoc* 2003;31:835–41.
10. Sukovic P. Cone beam computed tomography in craniofacial imaging. *Orthod Craniofac Res* 2003; discussion 6 Suppl 1 179–182;31–36.
11. Wortche R, Hassfeld S, Lux CJ, Müssig E, Hensley FW, Krempien R, et al. Clinical application of cone beam digital volume tomography in children with cleft lip and palate. *Dentomaxillofac Radiol* 2006;35:88–94.
12. Ludlow JB, Davies-Ludlow LE, Brooks SL. Dosimetry of two extraoral direct digital imaging devices: NewTom cone beam CT and Orthophos Plus DS panoramic unit. *Dentomaxillofac Radiol* 2003;32:229–34.
13. Ludlow JB, Davies-Ludlow LE, Brooks SL, Howerton WB. Dosimetry of 3 CBCT devices for oral and maxillofacial radiology: CB Mercuray, NewTom 3G and i-CAT. *Dentomaxillofac Radiol* 2006;35:219–26.
14. Iwai K, Arai Y, Hashimoto K, Nishizawa K. Estimation of effective dose from limited cone beam x-ray CT examination. *Dent Radiol* 2000;40:251–9.
15. Tsiklakis K, Donta C, Gavala S, Karayianni K, Kamenopoulou V, Hourdakakis CJ. Dose reduction in maxillofacial imaging using low dose cone beam CT. *Eur J Radiol* 2005;56:413–7.
16. International Commission on Radiological Protection. Recommendations of the International Commission on Radiological Protection. ICRP Publication 103. Ann ICRP 37. Elsevier, 2007.
17. International Commission on Radiological Protection. 1990 Recommendations of the International Commission on Radiological Protection. ICRP Publication 60. Ann ICRP 21. Oxford, UK: Pergamon Press, 1991.
18. Hiles P, Mackenzie A, Scally A, Wall B. Recommended standards for the routine performance testing of diagnostic X-ray imaging systems. IPEM Report No. 91. York, UK: Institute of Physics and Engineering in Medicine, 2005.
19. National Radiological Protection Board (NRPB). Living with radiation. National Radiological Protection Board. Didcot, UK: NRPB, 1998.
20. Martin CJ. Effective dose: how should it be applied to medical exposures? *Br J Radiol* 2007;80:639–47.
21. Nakajima A, Sameshima GT, Arai Y, Homme Y, Shimizu N, Dougherty H Sr. Two- and three-dimensional orthodontic imaging using limited cone beam-computed tomography. *Angle Orthod* 2005;75:895–903.
22. Mah JK, Danforth RA, Bumann A, Hatcher D. Radiation absorbed in maxillofacial imaging with a new dental computed tomography device. *Oral Surg Oral Med Oral Pathol Oral Radiol Endod* 2003;96:508–13.
23. Shrimpton PC, Hillier MC, Lewis MA, Dunn M. Doses from computed tomography (CT) examinations in the UK – 2003 Review. Report No. NRPB-W67. Chilton, UK: NRPB, 2005.
24. Isaacson KG, Thom AR. Orthodontic Radiographs – Guidelines. London, UK: British Orthodontic Society, 2001.
25. Pendlebury ME, Horner K, Eaton KA. Selection Criteria for Dental Radiography. 2nd edn. London, UK: Faculty of General Dental Practitioners, 2004.
26. National Radiological Protection Board. Occupational, Public and Medical Exposure. Documents of the NRPB. Didcot, UK: NRPB, 1993/4.