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Cone-beam computerized tomography (CBCT) imaging of the oral and maxillofacial region: A systematic review of the literature

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Abstract. This study reviewed the literature on cone-beam computerized tomography (CBCT) imaging of the oral and maxillofacial (OMF) region. A PUBMED search (National Library of Medicine, NCBI; revised 1 December 2007) from 1998 to December 2007 was conducted. This search revealed 375 papers, which were screened in detail. 176 papers were clinically relevant and were analyzed in detail. CBCT is used in OMF surgery and orthodontics for numerous clinical applications, particularly for its low cost, easy accessibility and low radiation compared with multi-slice computerized tomography. The results of this systematic review show that there is a lack of evidence-based data on the radiation dose for CBCT imaging. Terminology and technical device properties and settings were not consistent in the literature. An attempt was made to provide a minimal set of CBCT device-related parameters for dedicated OMF scanners as a guideline for future studies.

Keywords: cone-beam CT; oral and maxillofacial imaging; radiation dose; systematic review.

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Cone-beam computerized tomography (CBCT) is a medical image acquisition technique based on a cone-shaped X-ray beam centered on a two-dimensional (2D) detector. The source-detector system performs one rotation around the object producing a series of 2D images. The images are reconstructed in a three-dimensional (3D) data set using a modification of the original cone-beam algorithm developed by Feldkamp et al.[34] in 1984. This technique is widely used in different industrial and biomedical applications such as micro-CT. Among the first clinical applications were single photon emission computerized tomography (SPECT), angiography and image-guided radiotherapy. Dedicated CBCT scanners for the oral and maxillofacial (OMF) region were pioneered in the late 1990s indepently by Arai et al.[6] in Japan and Mozzo et al.[111] in Italy. Since then there has been an explosion of interest in this new imaging technique in the OMF region by different research groups. The rapid evolution of the first prototypes into faster and better dedicated scanners has been driven by the development of new detector technology and by the increasing data processing power of common commercially available personal computers.

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Although some papers provide a synopsis[11,15,21,24,25,32,37,39,40,42,65,72,94,98,113,123,126,128,139,148,155,162,172,173,175] on the use of CBCT imaging in the OMF region, a systematic review has not been published. The authors carried out a systematic review of the literature on CBCT imaging in the OMF region to evaluate data on clinical applications, technical parameters and radiation dose and to define a minimal set of CBCT device-related parameters as a guideline for future studies.

Materials and methods

The literature regarding CBCT imaging in the OMF region was systematically reviewed. A PubMed search (National Library of Medicine, NCBI, New Pubmed System; revised 1 December 2007) was conducted from 1 January 1988 to 1 December 2007. 11 central keywords (Table 1) related to CBCT were used in combination with a total of 50 additional keywords (Table 1) to limit the search to CBCT imaging of the OMF region with dedicated CBCT scanners. These key words were used as search terms in multiple searches, consisting of every possible combination of one central and an additional keyword. This initial search revealed 375 papers, which were screened in detail. An additional five papers[52,96,97,160,161] that could not be found using the cone-beam related keywords, but were relevant to the subject, were submitted to the study. Of this total study sample of 380 papers (Table 2), 81 were related to CBCT imaging in other fields outside the scope of this paper, such as angiography, micro-CT, SPECT and radiotherapy, and were not included in this study. 71 papers were primarily concerned with the science of CBCT and were excluded because they lacked clinical relevancy. 45 papers were excluded because they were not relevant to the subject and 5 were excluded because they were written in languages for which translation was not available (4 in Chinese and 1 in Japanese). One paper was excluded because it was not available. The study sample consisted of 177 clinically relevant papers that were analyzed in detail (Table 2).

These papers were placed in one of four groups (Table 3) according to their emphasis: clinical applications, technique, radiation dose, and synopsis papers. Papers related to two or more groups were assigned to every relevant group. This explains why the sum of the papers in each group is larger than the total number of papers and why the sum of the seperate percentages does not equal 100. Based on the results of this extensive systematic review, a minimal set of CBCT device-related parameters for dedicated OMF scanners is proposed as a guideline for future studies.

Table 1. Central and additional key words used as search terms in the systematic review on CBCT imaging of the OMF region.

Central key words	Additional key words
cone-beam	facial
conebeam	face
CB-CT	dental
CBCT	dentofacial
digital volume tomography	tooth
dvt	teeth
compact CT	maxillofacial
compact computed tomography	maxilla
volumetric CT	maxillary
volumetric computed tomography	mandible
ortho cubic	mandibular
	mandibula
	craniofacial
	skull
	cervical
	cranial
	intracranial
	extracranial
	zygomatic
	head
	neck
	oral
	jaw
	mouth
	palatal
	orthognathic
	orthodontic
	endodontic
	periodontic
	periodontal
	periodontology
	cleft
	cavity
	temporomandibular
	TMJ
	condyle
	condylus
	condylar
	implant
	sinus
	temporal
	brain
	dentolaveolar
	alveolar
	molar
	practice
	dentist
	dentistry
	ear
	nose

Table 2. Papers yielded by the PubMed search (National Library of Medicine, NCBI; revised 1 December 2007) on CBCT imaging of the OMF region.

Clinically relevant	177 (Table 3)
Other fields	81
Scientific	71
Not relevant	45
Other language	5
Not available	1
Total	**380**

Table 3. Clinically relevant papers on CBCT imaging of the OMF region that were analyzed in detail in this study.

Clinical applications	86*	49% (Table 4)
Technical related	65	37% (Table 6)
Radiation dose	16**	9% (Table 8)
Synopsis articles	26	15%
Total	**177**	**110%**

* Only clinically relevant articles dealing with patients were assigned to this group.

* * All clinically relevant articles mentioning 'tested' or 'calculated' dosimeter values were assigned to this group, except when those values were quoted from other publications.

Results

177 papers were analyzed. 86 papers (49%) were related to clinical applications, 65 (37%) to technique, 16 (9%) to radiation dose and 26 (15%) were synopsis papers (Table 3).

Clinical applications

86 papers dealt with clinical applications of CBCT imaging in the OMF region. All papers in which dedicated OMF CBCT scanners were used on patients in clinical situations were assigned to this group. The group was broken down into 9 clinical subcategories (Tables 4 and 5).

25 (29%) papers reported the use of CBCT imaging in the assessment of dento-alveolar pathology (Table 5); 14

Table 4. Papers related to clinical applications of CBCT imaging of the OMF region.

Dento-alveolar	25	29% (Table 5)
Maxillofacial surgery	35	41% (Table 5)
Orthodontics	14	16% (Table 5)
Implantology	11	13% (Table 5)
Endodontics[21,87,121,153]	4	5%
Periodontics[68,69,117]	3	3%
General dentistry[177]	1	1%
Forensic dentistry[179]	1	1%
Otolaryngology[22]	1	1%
Total	**86**	**110%**

Table 5. Details of four categories of clinical application in Table 4.

Dento-alveolar		
Impacted teeth[7,26,84,85,86,95,101,118,119,120,129,163,174,177]	14	56%
Surnumerary teeth[119,154,164]	3	12%
Dento-alveolar traumatology [19,21,164,177]	4	16%
Root resorption[18,21,84,127]	4	16%
Foreign body[84,168]	2	8%
Other[21,138,141,156]	4	16%
Total	**25**	**124%**
Maxillofacial surgery		
Temporomandibular joint[60,61,63,73,100,120,145,166,177]	9	26%
Odontogenic cysts & tumours[8,119,164,180]	4	11%
Traumatology[12,54,84,164,180]	5	14%
Cleft pathology[7,43,77,108,112,176]	6	17%
Orthognathic surgery[13,14,160,161]	4	11%
Intra-operative imaging[51–53,77]	4	11%
Navigation[107,134,181]	3	9%
Oral cancer[17,180]	2	6%
Osteomyelitis[38,149]	2	6%
Bisphosphonate related ONJ[79]	1	3%
Obstructive sleep apnea[124,125]	2	6%
Total	**35**	**120%**
Orthodontics		
Miniscrews[41,74,75,133]	4	29%
Cephalometry[33,80,81]	3	21%
Tooth position[31,112,130]	3	21%
Other[1,16,142,152]	4	29%
Total	**14**	**100%**
Implantology		
Planning[7,48,67,109,147,164]	6	55%
Surgical guidance template[5,122]	2	18%
Other[21,50,180]	3	27%
Total	**11**	**100%**

(56%) dealt with the preoperative assessment of impacted teeth: 8 with impacted canines[7,85,86,95,101,163,174,177], 5 with third molars[26,84,118,119,129], 1 with mesiodens[84] and 1 with a maxillary second premolar[120]. 3 (11%) papers dealt with supernumerary teeth[119,154,164]. 4 (16%) papers described the use of CBCT in the assessment of dentoalveolar traumatology[19,21,164,177], 4 (16%) focused on root resorption[18,21,84,127], 2 (8%) dealt with foreign bodies[84,168]. 1 (4%) paper investigated the vestibular surgical access for apicectomy of the palatal root of the superior first molar[138]. 3 (12%) papers were case reports on the identification of double mandibular canals[141], an anterior mandibular lingual salivary gland defect[156], and an enlarged incisive foramen presenting as an apical lesion[21].

35 (41%) papers dealt with the use of CBCT imaging in maxillofacial surgery (Table 5). In 9 (26%) papers, CBCT imaging was performed to assess the temporomandibular joint (TMJ) mainly for diagnostic purposes[61,120,145,166], but also for arthrography[63,177] and for measuring the thickness of the glenoid fossa[73,100]. In 1 paper[60], CBCT was used for an image-guided puncture technique of the TMJ. 4 (11%) papers described the use of CBCT in the assessment of odontogenic cysts and tumours; there was a case report of a myxoma[8], an ameloblastoma[180], a radicular cyst[164] and a case report on a cementoma and an odontoma[119]. 5 (14%) papers reported CBCT imaging in maxillofacial trauma, mainly for mandibular fractures[84,164,180], but also for facial trauma[12,54]. CBCT was used to assess cleft pathology in 6 (17%) papers mainly for general assessment of the cleft region[7,77,112,176], but also to evaluate an alveolar bone graft[43] and to assess nasal deformity and the bony depression of the piriform margin[108]. 4 (11%) papers described the use of CBCT imaging in orthognathic surgery[13,14,160,161], and another 4 (11%) in intra-operative imaging[51–53,77]. In 3 (9%) papers CBCT was used to support navigation surgery[107,134,181]. There were 2 (6%) papers on CBCT imaging of the mandible in oral cancer patients[17,180], and another 2 (6%) on the assessment of osteomyelitis[38,149]. In 1 paper, CBCT was used to assess bisphosphonate related osteonecrosis of the jaw[79]. There were 2 (6%) papers on the use of CBCT in obstructive sleep apnea[124,125].

14 (16%) papers dealt with the use of CBCT imaging in orthodontics (Table 5). In 4 (29%) papers CBCT imaging was used in the field of miniscrews; in 2 papers palatal bone thickness was assessed[41,75]; in 1 paper the safe zones for miniscrews in the maxillary and mandibular arches were determined[133] and 1 paper dealt with the use of CBCT imaging to fabricate surgical guides for miniscrew placement[74]. CBCT imaging was used for cephalometry in 3 (21%) papers[33,80,81]. In another 3 (21%) papers, tooth position[112] or inclination[31,130] was assessed with the use of CBCT imaging. CBCT was reported for the assessment of rapid maxillary expansion[142], determination of skeletal age based on cervical vertebrae morphology[152], incidental findings in orthodontic patients[16] and 3D evaluation of upper airway anatomy in adolescents[1].

11 (13%) papers dealt with the use of CBCT imaging in implantology (Table 5). In 6 (55%) papers CBCT imaging was used to assess the region of interest (ROI) for dental implant planning[7,48,67,109,147,164]. 2 (18%) papers described the fabrication of surgical guidance templates with the use of CBCT data[5,122], while in 1 paper CBCT imaging was used for navigation during implant placement[50].There were two case reports on the use of CBCT imaging for diagnosis of an antral floor perforation[180] and evaluation of a peri-implant defect[21].

4 (5%) papers dealt with the use of CBCT imaging in endodontics and described the assessment of periapical pathology with CBCT[21,87,121,153].

3 (3%) papers reported CBCT imaging in periodontics; in 2 papers CBCT imaging was used to assess periodontal breakdown[69,117] and in 1 paper the outcome of regenerative periodontal therapy was evaluated[68].

1 (1%) paper mentioned the clinical use of CBCT in general dentistry where it was used for imaging caries lesions[177]. Another paper (1%) reported the use of CBCT in forensic dentistry and dealt with

Table 6. Papers related to technique of CBCT imaging of the OMF region.

Accuracy	28	43% (Table 7)
Objective evaluation of image quality	10	15% (Table 7)
Subjective evaluation of image quality	23	35% (Table 7)
Feasibility[30,135,136,137,160,161]	6	9%
Artifacts[27,58,70,71]	4	6%
Web-based education[4,47]	2	3%
Total	**65**	**111%**

Table 7. Details of three categories of technique in Table 6.

Accuracy		
General linear measurements[76,82,88,89,93,109,132]	7	37%
Specific linear measurements[3,56,59,66,78,102–104,110,171]	10	53%
Quantitative measurements[9,83,90,116]	4	21%
Transfer to surgical field[36,146,170]	3	16%
Postprocessing[2,13,90,105,132,152]	6	21%
Total	**28**	**148%**
Objective evaluation of image quality		
Resolution[6,7,10,136,159]	5	50%
Distortion[7,90,99,111]	4	40%
Noise[7,10,20,136]	4	40%
Total	**10**	**130%**
Subjective evaluation of image quality		
Overall anatomic image performance[44–46,58,89,106,115,150]	8	35%
Specific diagnostic capability[23,28,29,35,49,57,62,64,102,103,131,137,157,158,167]	15	65%
Total	**23**	**100%**

dental age estimation[179]. In 1 (1%) paper CBCT imaging was used in the field of otolaryngology to assess temporal bone anatomy[22].

Technique related

The second group consisted of 65 papers related to technique. All papers in which CBCT imaging was used in vitro (human cadavers, head phantoms, anatomical specimens, extracted teeth, geometrical objects, anonymous clinical datasets) to evaluate its performance, features and usefulness were assigned to this group. This group was broken down into 6 technical subcategories (Tables 6 and 7).

28 (43%) papers evaluated the accuracy of CBCT imaging. 7 (37%) papers assessed the accuracy of general linear measurements[76,82,88,89,93,109,132] by using a cursor to select points on acquired CBCT datasets and measure the distance between them, after which the results were compared with measurement data acquired using other image acquisition techniques or caliper measurements. 10 (53%) papers dealt with the accuracy of CBCT in specific measurements. In 3 papers, the accuracy of CBCT in the measurement of periodontal defects was tested[102,104,171]. There were 2 papers on the accuracy of cephalometric measurements[78,110] with CBCT. 2 papers evaluated the accuracy of measurements in the TMJ area[56,59] while the other 3 papers tested its accuracy in caries lesions[3], peri-implant defects[103] and the location of the genial tubercle[66]. 4 (21%) papers assessed the accuracy of CBCT for quantitative measurements of bone density[9,83,90,116]. The accuracy of implant placement based on pre-surgical planning with CBCT imaging was investigated in 3 (16%) papers; 2 papers reported the use of stereolithographic drill guides[146,170] and one reported a robotic drilling machine[36] for implant placement.

10 (15%) papers reported objective evaluation of the image quality of CBCT by providing values for image quality characteristics. In 5 (50%) papers the image quality of CBCT was reported in terms of resolution[6,7,10,136,159]. In 4 (40%) papers, distortion or geometric accuracy of CBCT imaging was measured[7,90,99,111]. 4 (40%) papers reported CBCT image performance related to noise[7,10,20,136].

Subjective evaluation of image quality of images acquired with CBCT, was dealt with in 23 (35%) papers. In these articles, the image quality was individually scored on a scale by different observers. In 8 (35%) papers the general anatomical image quality was assessed[44–46,58,89,106,115,150]. 15 (65%) papers investigated in vitro the specific diagnostic capability of CBCT imaging for various clinical purposes: temporal bone anatomy[23], middle ear imaging[131], frontal bone anatomy[137], detectability of foreign bodies[28,29], evaluation of midface osteosynthesis[35], imaging of cervical soft tissue[49], anatomy of the TMJ[57,62,64], assessment of periodontal breakdown[102], peri-implant defects[103], periapical pathology[158], caries lesions[167] and the evaluation of root fillings[157].

6 (9%) papers were feasibility reports related to CBCT imaging. 2 papers described the feasibility of a virtual augmented model for orthognathic surgery[160,161] while 1 paper mentioned the future use of CBCT imaging in the setup of a virtual craniofacial patient model[30]. In 1 paper the feasibility of a virtual autopsy with the use of CBCT imaging was discussed[135]. 2 papers investigated the feasiblility of CBCT for intraoperative imaging and guidance in temporal bone surgery[136] and frontal bone surgery[137].

4 (6%) papers addressed the artifacts present in CBCT images; in two of these papers the presence of artifacts was evaluated and scored by different observers[27,58]. The other 2 papers addressed CBCT artifacts in a more extensive way by providing values for density variation due to artifacts[71] as well as parameters that influenced the presence and intensity of these artifacts[70]. 2 (3%) papers reported the use of CBCT datasets to provide clinical images for a web-based instruction module to educate dental professionals[4,47].

Radiation dose

The third group consisted of 16 papers related to the radiation dose of OMF dedicated CBCT scanners. All clinically relevant articles mentioning 'tested' or 'calculated' dosimeter values were assigned to this group, except when those values were quoted from other publications. Table 8 provides an overview of the different values reported in the clinical literature.

2 papers from the same research group provided dosimetry values that were calculated and reported in different ways. In the first paper, an OMF CBCT scanner was compared with a panoramic X-ray unit[91], while in the second paper a comparison of three CBCT devices was made[92]. One paper compared radiation exposure in panoramic radiography, low dose dental multi-slice CT (MSCT) and CBCT[20]. Two papers compared dosimetry values of CBCT with dental MSCT[97,151]. In 4 papers a new CBCT device was introduced and some radiation dose values were given[6,44,111,159]. In one of those

Table 8. Reported radiation dose values of CBCT imaging of the OMF region.

Apparatus and settings (if provided)	Absorbed dose (mGy)		Effective dose (μSv)		Dose as a percentage of annual background radiation		Dose as a multiple of single panoramic dose[92]		Effective dose (μSv) Unknown****
	TLD range	Unknown	IRCP 1990	IRCP 2005	IRCP 1990	IRCP 2005	IRCP 1990	IRCP 2005	
3D Accuitomo (2 mA)[131] (2 mA/17.5 s)		1.4							13
3DX Multi image Micro CT[44] (2 mA/17 s)		1.19*							
NewTom 3G 12″ FOV[92] (1.5 mA/5.4 s)			44.7	58.9	1.2	1.6			
CB Mercuray 12″ FOV – 100 kV[92] (10 mA/10 s)	10.90–11.30		476.6	557.6	13.2	15.5	74	42	
CB Mercuray 12″ FOV – 120 kV[92]			846.9	1025.4	23.5	28.5	132	78	
CB Mercuray 9″ FOV[92]			288.9	435.5	8	12.1	45	33	
CB Mercuray 6″ FOV (maxillary)[92]			168.4	283.3	4.7	4.9	26	21	
i-CAT 12″*** FOV[92] (5.7 mA/6.6***s)			134.8	193.4	3.7	5.4	21	15	
i-CAT 9″ FOV[92]			68.7	104.5	1.9	2.9	11	8	
NewTom QR-DVT 9000 (6.5 – 8.2 mA/18 s)[20]	0.1–4.1		42.1	91.5					100–110
NewTom QR-DVT 9000 (3.4 mA/17 s)[165]	0.32–1.67		35						
NewTom QR-DVT 9000 9″ FOV (3.2 mA/18 s)[91]	0.37–1.79		36.9	51.7	1.0	1.4	6	4	
NewTom QR-DVT 9000 (5.4 mA/18 s)[176]				342**					
NewTom 9000 (3.5 mA/18 s)[97]	0.044–1.400		50.27						
NewTom 9000 (122-155 mA/76 s)[151]	4.06–5.92								
DentoCAT [159] (110 kV)									585
Ortho-CT (3DX prototype) (10 mA/17 s)[6]		0.62							
Galileos prototype 9″ FOV[107]			47.0	62.0	1.3	1.7	7	5	
Siemens PowerMobil at 1/2 resolution[136,137]		0.4–5.6							
SireMobil (59-72 kV, 18 s, 2.5-3.5 mA/shot)[151]	0.97–3.01								
Panoramic OrthoPhos Plus[92]			6.3	13.3	0.2	0.4	1	1	
MaxMand CT Scan[92]			2100		58.3		336		

* [44]absorbed dose reported in mSv instead of mGy.

** [176]IRCP version not reported.

*** involves two 9″ field of view (FOV) scans.

**** calculation not provided.

Dosimetry values are only provided in the way they are literally reported in the papers included in this study. The authors did no calculations or conversions to complete the table. The dose values in the 'TLD range' column are the smallest and biggest radiation dose values measured by the TLDs at different anatomic locations in one phantom. In the last two rows, two other imaging modalities were added for comparison. These values were extracted from Ludlow et al.[92], which was cited the most in the clinical literature on radiation dose of CBCT of the OMF region.

papers[111], radiation dose values were provided in a way that they could not be included in Table 8. The use of a thyroid-shielding technique to lower the CBCT radiation dose was described in another paper[165]. There was one elaborate paper in which CBCT dose was measured and compared with other imaging modalities specifically for cleft patients[176]. In one paper about the use of CBCT in intraoperative imaging, dosimetry values of the CBCT device used were compared with other CBCT devices[107]. The effect of radiation dose on image quality and the different images provided by acquisition with different radiation doses were discussed in another paper[137]. One paper on CBCT imaging of the middle ear also provided radiation dose values[131]. In one paper about dose reduction in dental MSCT, CBCT radiation dose was discussed but no new values for CBCT were reported[143].

Synopsis articles

This group consisted of 26 papers. All papers that did not present the results of a study, but provided the reader with a general overview or a more particular aspect of CBCT in the OMF region, were assigned to this group. Most of these synopsis papers introduce the reader to the new technology of CBCT, often with an emphasis on its applications in one or more particular clinical areas such as orthodontics[11,72,98], implantology[39,40,42,175], endodontics[21,113,128] and dentistry in general[24,25,65,126,148,155]. One paper[139] described the benefits and limitations of CBCT imaging in children. Three interesting papers discussed craniofacial imaging[96,173] or craniofacial computed tomography[172] in general. Another paper pointed out some legal implications of CBCT imaging in the OMF region[94]. One paper discussed the indications of digital transversal slice imaging in general[37] while another elaborately described the Digital Imaging and Communications in Medicine (DICOM) system, which is important in CBCT imaging[32]. One paper described the fusion of CBCT images with 3D images acquired with optical sensors[123]. One paper discussed the possibilities of comparing voxel-based 3D CBCT images for diagnostic objectives[15]. One paper described the potential of CBCT imaging for 3D cephalometry[162].

Discussion

Since the introduction of dedicated dentomaxillofacial CBCT scanners in the late 1990s[6,111], there has been an explosion of interest in these devices in the field of OMF surgery, orthodontics and dentistry. In the last decade, the number of CBCT related papers published each year has increased (Fig. 1). This results in a vast amount of literature. A systematic review of the literature related to CBCT imaging of the OMF region was undertaken to evaluate the indications, benefits and drawbacks of this new image acquisition technique.

During the set-up of the study design for this systematic review, it became obvious that there were few conventions for reporting unambigously on this subject. At the time of the PubMed search, there was no MeSH term available for CBCT. Combinations of 11 central and 50 additional keywords (Table 1) were used as search terms in this systematic review on CBCT imaging of the OMF region to include all relevant articles. Other terminology encountered in the literature, such as cone beam volumetric scanning (CBVS), true volumetric computed tomography, dental CT, dental 3D-CT, cone beam volumetric imaging (CBVI) did not result in additional relevant papers. A MeSH term for CBCT has become available without including 'digital volume tomography (DVT)', which is a commonly used term in papers published by German research groups. There was inconsistency and discrepancy in how the CBCT device settings, properties and radiation dose (Table 8 and 9) were reported in the different papers, which confuses the reader. There was also inconsistency in how the CBCT acquisition protocol was reported, which is crucial since device settings, image quality and the resulting radiation dose are closely related.

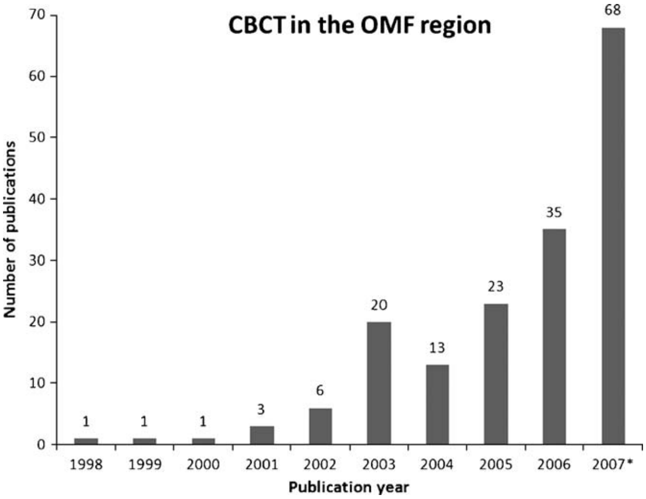

Fig. 1. Distribution of published articles on CBCT in the OMF region yielded by the PubMed search (National Library of medicine, NCBI; revised 1 December 2007). * Publications until 1 December 2007.

The clinical applications for CBCT imaging in the OMF region are increasing. The results of this study showed that 86 papers dealt with the clinical applications of CBCT in dento-alveolar and maxillofacial surgery, implantology, general dentistry and specialised dentistry (orthodontics, endodontics, periodontics, forensic dentistry) and otolaryngology (Table 4). The most common clinical applications were impacted teeth (Table 5) and implantology (Table 5). The American Association of Oral and Maxillofacial Radiology has stated that cross-sectional views are recommended for planning dental implants[169], this in combination with the easy accessibility, easy handling and low radiation dose of CBCT imaging, will lead to the widespread use of CBCT imaging in implantology. Growth is also expected in the clinical fields listed in Table 4.

Analysis of the papers related to technique (Table 6) showed that in almost every article that assessed image performance of CBCT in vitro or in vivo, interpretation of the results and conclusions was based on comparison of CBCT with other imaging acquisition modalities such as MSCT or intra-oral radiography. Depending on the type, model or version of the imaging apparatus used for comparison, different and sometimes opposite conclusions were made on which of these image acquisition techniques is the most suitable for a certain clinical indication. Papers in which older CBCT units were compared with MSCT, frequently scored the overall subjective image quality higher in MSCT than in CBCT[58]. The opposite was observed in papers where more recent

Table 9. Reported settings of different CBCT apparatus used in CBCT imaging of the OMF region.

	NewTom QR- DVT 9000	PSR 9000	3D Accuitomo (3DX)	Arcadis Orbic 3D	NewTom 3G	i-CAT	CB Mercuray
Manufacturer	Quantitative Radiology, Verona, Italy	Asahi Roentgen, Kyoto	J. Morita, Kyoto	Siemens Medical Solutions, Erlangen	Quantitative Radiology, Verona, Italy	Imaging Sciences, Hatfield, PA	Hitachi Medical, Kyoto
References	1,9,13,14,19,20,25,27,28,29,30, 31,35,36,42,48,54,55,58,75,77, 82,85,86,90,91,93,97,99,100, 101,111,112,122,124,125,129, 130,133,138,140,141,149,150, 165,166,174,176,180,181	42,43,74,76,118,119	2,3,8,21,22,23,25,42,44,59, 60,62,66,68–73,84,87–90,102, 109,115,116,117,120,121,131, 144,145,154,157,163,167, 168,170,179	50,77,134	18,19,25,41,57,72, 77,78,80,92,142, 153,158	5,25,33,39,42,56,64, 72,90,92,104,110,127, 132,146,152,156,171	7,25,42,72,92,108,178
Tube Voltage (kV)	110 (fixed) 85	80 60-100 (1 kV step)	60-80 (1 kV step) 85	40-110	110	120	60-120 (20 kV step) 70-100
mA	0.8-15 3.5 (fixed) 10-15 0.5-10 up to 15	10 2-12 (2 mA step)	1-10 1-10 (0.1 mA step)	0.2-15.2 up to 23	1.5 0.5	5.7 1-3 3-8 5-8	10 or 15 up to 15
Grayscale Depth	8 bit 12 bit		8 bit 12 bit		12 bit	12 bit	8 bit 12 bit
Exposure control	automatic smart scan				automatic smart scan	fixed automated	operator
Exposure time (s)	18 36	20.48	17.5 17		5.4 5-7	6.6 4.6	9.6 10.0
Scan Time (s)	70-76 78	20 30	17 (360°) or 9 (180°) 17.5 18	30 or 60		40 20 10	10
Radiation Source	pulsed			pulsed		pulsed	
Exposure time per image (s)					0.015	0.011	0.035
Exp arc subtended/image					0.15°	0.20°	1.25°
Rotation	360°		360 or 180	190°	360°	360°	360°
Projections per rotation	360	365	510	50 or 100		306	288
Detector Type	II - CCD		II - CCD	II		FPD	CCD II
Detector Size	8″ × 8″ 400 cm^2		10 cm diameter 4″	9″	9″	20 × 25 cm	F)12″ or P)12″/9″ or I) 12″/9″ or D)9″ *
Amplification	22:1						
Cone beam angle	14°			9°			
FOV	230 × 230 mm 9″				12″or 9″ or 6″	12″** or 9″	F) 192.5 mm or P) 150.0 mm or I) 102.4 mm or D) 51.2 mm *
Slice Thickness (mm)	0.33 0.3-1	0.117	0.125 - 2		0.5	0.4	
Voxel Size (x.y.z)	0.28 mm 0.3 mm	0.117 0.1 mm	0.125 mm 0.125 × 0.125 × 1.000			0.2–0.4 mm 0.25	F) 0.376 mm or P) 0.293 mm or

Table 9 (*Continued*)

	NewTom QR- DVT 9000	PSR 9000	3D Accuitomo (3DX)	Arcadis Orbic 3D	NewTom 3G	i-CAT	CB Mercuray
Manufacturer	Quantitative Radiology, Verona, Italy	Asahi Roentgen, Kyoto	J. Morita, Kyoto	Siemens Medical Solutions, Erlangen	Quantitative Radiology, Verona, Italy	Imaging Sciences, Hatfield, PA	Hitachi Medical, Kyoto
	0.25 mm 0.07–0.0265 mm 0.25 × 0.25 × 0.3	0.1–0.15	0.119 mm^3 0.136				I) 0.200 mm or D) 0.100 mm *
Scanned Volume Dimensions	12 cm × 15 cm	B) 42.7 × 30 × 30 mm or	4 × 3 or 4 × 4 or 6 × 6		8 × 8 or 10 × 10 or 13 × 13 or 15 × 15 or 18 × 18 or 22 × 22	17 × 13.2 cm	5.12 × 5.12 or 10.2 × 10.2 or 15 × 15 or 19 × 19
	13 × 13	P)5 scans/mandible				16 × 21 or 16 × 13 or 16 × 8	
		3.6 × 4 or 4.1 × 4					
Scanned Volume Height	10 cm 110 mm 13 cm		30 mm 23 mm 60 mm		22 cm	17 cm 11 cm	
Scanned Volume Diameter	12–13 cm 150 mm		40 mm 38 mm 60 mm		25 cm	17	
Pixel Set	752 × 582		320 × 240			1024 × 1024	512 × 512 × 512
	512 × 512		280 × 240 512 × 512				
Patient Positioning	supine		seated	operating table	supine		
Proprietary Software	-NewTom 9000 Dental reconstruction software		-Accuitomo i-Dixel -3DX Integrated Information System -i-View		-NNT Newtom 3G	-iCAT acquisition software	-CB Works
Total Filtration	0.7 - 8.0 mm Al		3.1 mm Al 31 mm Al				
Front panel attenuation				>3 mm Al		1 mm Al	
Software used	- 3D-Doctor (Able Software)[1] Impax (Agfa)[9] - Insight SNAP[13] -MIRIT[13] -VALMET[13] -Osiris[20] -TomoCon(TatraMed)[28,29] -eFilm Workstation[35,75,149] -Simgram[35]	-ULTRA2(Sun)[43] -VIP station imaging software[43]	-Visualization toolkit (Kitware Inc.)[2] -Tool command language toolkit[2] -LiveWire[2] -Vox Blast[115] -Image J Software (NIH)[167] - Oralim (Medicim) and ProCera (Nobel Biocare)[170] -Amira 3D (Mercury Computer System)[42]	-Fluor3D (BrainLab)[134]	-Dolphin 3D[78] -AMIRA (Mercury Computer Systems)[80] -Open-Source (OsiriX Medical Imaging Software)[142]	-3DVR (ISI)[38] -Analyze (Direct Inc.)[132] -Mimics and Simplant[146]	

	-AMIRA[124]				
Rotation centre to focal spot (mm)		335			820
Rotation centre to detector (mm)					290
Detector to focal spot (mm)		635		675	
Nominal focal spot (mm)			0.6	0.5	
3D Image Processing					MPR,VR,SR,MIP
Data Output					DICOM3.0,BMP, JPG,TIFF

	Ortho - CT	Galileos	Powermobil modified	Siremobil Iso-C 3D	DentoCat	CB Throne	PreXion 3D
Manufacturer	Scanora, Soredex, Helsinki	Sirona Dental Systems, Bensheim	Siemens	Siemens Medical Solutions	Xoran Technologies	Hitachi	TeraRecon, San Mateo, CA
References	[6,61,67,147,164]	[105–107]	[49,135,136]	[51–53,150]	[159]	[177]	40
Tube Voltage (kV)	85	90	100		110	60-120 (20 kV step)	
mA	10	7–28	4.6			10 or 15	
Grayscale Depth		12 bit					
Exposure control		operator					
Exposure time (s)	17			18 36			
Scan Time (s)	17	14	30 or 60	120 240			
Radiation Source							
Exposure time per image (s)		0.01-0.04					
Exp arc subtended/image							
Rotation	360°	200°	190°			360°	
Projections per rotation	512	200	200-500	100		288	512 or 1024
Detector Type	II	II-CCD	FPD				
Detector Size	4″	9″ 23 cm	40 cm × 30 cm			4″ 7″	
Amplification							
Cone beam angle							
FOV		15 cm 6″	20 × 20 × 15 cm 20.5 × 20.5 × 15.4				
Slice Thickness (mm)							
Voxel Size (x.y.z)	0.136 mm^3	0.30 mm^3 or 0.15 mm^3				D) 0.1 mm or	

Table 9 (*Continued*)

	Ortho - CT	Galileos	Powermobil modified	Siremobil Iso-C 3D	DentoCat	CB Throne	PreXion 3D
Manufacturer	Scanora, Soredex, Helsinki	Sirona Dental Systems, Bensheim	Siemens	Siemens Medical Solutions	Xoran Technologies	Hitachi	TeraRecon, San Mateo, CA
						I)0.2 mm *	
Scanned Volume Dimensions		15 × 15 × 15 cm					
Scanned Volume Height	32 mm	15 cm					
Scanned Volume Diameter	38 mm	15 cm				D) 2″ or I) 4″ *	
Pixel Set	280 × 240	512 × 512 or 1024 × 1024				512 × 512 × 512	
Patient Positioning	seated	standing or seated		operating table			
Proprietary Software				-SYNGO		-CB Works	
Total Filtration	1 mm Cu 1.2 mm Cu				0.4 mm Cu + 1 mm of Al		
Front panel attenuation							
Software used		-AMIRA[105]		-eFilm (Merge)[51,53]			
Rotation centre to focal spot (mm)							
Rotation centre to detector (mm)							
Detector to focal spot (mm)							
Nominal focal spot (mm)							
3D Image Processing						MPR, VR, SR, MIP, cross sectional, partial panoramic	
Data Output							

*: different modes.
**: involves two 9″ FOV scans.
Values were taken over from the references mentioned in each column without any changes. When no unit was reported, the value without the unit was added. When different values were reported in different articles, these were listed. Custom settings on the same CBCT unit are separated by ‘or’.

CBCT units with higher resolution were used for comparisons[46]. Although new CBCT scanners with flat panel detectors seem to be less prone to beam hardening artefacts such as metal artifacts, some important problems, such as susceptibility to movement artifacts, remain. Another problem is that, because of distortion of Hounsfield Units (HU, CT number), CBCT can not be used for the estimation of bone density. At the time of the introduction of the NewTom 9000 in 2000, Mozzo[111] stated that distortion of CT number was of no interest since no quantitative analysis was performed. In some papers[9,39,83,90] it has been suggested that CBCT can be used to assess bone density and to determine HU. This leads to some concern, because this is not the case, since scanned regions of the same density in the skull can have a different grayscale value in the reconstructed CBCT dataset[70,71,162]. Swennen and Schutyser[162] stated that with CBCT, the image value of a voxel of an organ depends on the position in the image volume. This means that the X-ray attenuation of CBCT acquisition systems currently produces different HU values for similar bony and soft tissue structures in different areas of the scanned volume (e.g. dense bone has a specific image value at the level of the menton, but the same bone has a significantly different image value at the level of the cranial base). Vannier[172] stated that when new developments in the synthesis and optimization of CBCT reconstruction algorithms allow the full exploitation of the potential of area detectors in CBCT, CBCT will provide important benefits for craniofacial imaging. It is expected that improvements in cone-beam reconstruction algorithms and postprocessing will solve or reduce this problem[162].

Table 10. Minimal set of parameters for OMF CBCT scanners recommended for future studies based on the results of this systematic review.

Manufacturer	trade name, company, city, country, website
Tube voltage	killovolt (kV)
Tube current	milli-ampere (mA)
Tube current x Exposure time	milli-ampere x seconds (mAs)
Grayscale depth	bit
Exposure time	seconds (s)
Scan time	seconds (s)
Radiation source	pulsed/not pulsed
Rotation	degree (°)
Projections per rotation	number (n)
Detector type	type
Detector size	cm
Field of view (FOV)	cm x cm
Voxel size (x,y,z)	mm^3
Scanned volume dimensions	cm x cm x cm
Matrix (pixel set)	pixel x pixel
Patient positioning	supine/seated/standing
Rotation centre to focal spot	mm
Data output	DICOM(+version)/JPG/TIFF/BMP
Radiation dose*	milli-sievert (mSv) or micro-sievert (μSv)

* ICRP version used to calculate the radiation dose should be mentioned.

As far as the radiation dose of CBCT imaging is concerned, it is crucial that the ALARA principle (radiation dose 'As Low As Reasonably Achievable') is respected. It is important that the different relevant parameters are rigorously and consistently reported. This review showed that many papers did not supply sufficient information regarding the CBCT device settings and properties, which is important regarding radiation dose, image quality and reproducibility. Table 9 illustrates the discrepancies between certain parameters, especially exposure time, scan time, field of view, detector size, scanned volume and pixel set. A minimal set of CBCT device-related parameters for dedicated OMF scanners was therefore proposed as a guideline for future studies based on the results of this study (Table 10). Because CBCT scanners have a unique radiation geometry, no conventions on how CBCT dosimetry should be measured in terms of radiation detector setup in phantoms and geometrical calculation have yet been agreed. As a result, most research groups use the same experimental setup as for MSCT dosimetry. The results of this systematic review showed that papers dealing with radiation dose often provided comparative data from other image acquisition modalities such as MSCT (e.g. MaxMand CT Scan: effective dose of 2100 according to ICRP 1990[183]) and panoramic radiography (e.g. panoramic OrthoPhos Plus: effective dose of 6.3 and 13.3 according to ICRP 1990 and 2005, respectively[91]). CBCT provides less radiation than MSCT and more than a panoramic X-ray, but the results of this study showed important discrepancies in the reported restriction of the radiation dose by CBCT because of the large differences in MSCT dosimetry values that were used for comparison, as well as in the CBCT dosimetry values themselves.

The radiation dose of devices used in a clinical environment on patients should be reported in milli-sievert (mSv) or micro-sievert (μSv), to express the effective *dose* (E). As Ludlow[91] stated, the effective radiation dose has been recommended by the ICRP (International Commission on Radiological Protection) [182] as a means of comparing detriment of different exposures to ionizing radiation to an equivalent detriment produced by a full-body dose of radiation. The effective dose should be calculated using the equation $E = \sum w_T \cdot H_T$, 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 equivalent dose (H_T) should be calculated using the equation $HT = \sum w_R \cdot D_T$, where the equivalent dose (H_T) for a tissue or organ is expressed as a product of the radiation weighting factor (w_R) (which is 1 in the case of X-ray radiation) and the measured absorbed dose (D_T) averaged over a particular tissue or organ.

Tissue weighting factors are provided by the ICRP. Two ICRP versions are reported in the literature, the 1990[183] and the 2005[184] versions, which result in different values when the effective dose is calculated. It is crucial that authors or manufacturers of CBCT devices report the ICRP version they used to calculate the radiaton dose. Many authors only used absorbed dose to express the radiation dose of a particular CBCT device in milli-gray (mGy), which is irrelevant for the clinician, because it does not take into account the relative contribution of the different organs and tissues to the overal risk of radiation detriment.

The benefits and limitations of CBCT imaging in the OMF region are listed in Table 11. The main advantages of CBCT imaging are its accessibility, easy handling and that its offers a real-size dataset with multiplanar cross-sectional and 3D reconstructions based on a single scan with a low radiaton dose. Patel et al.[128] stated that perhaps the most clinically useful aspect of CBCT imaging is the highly sophisticated software that allows the huge volume of data collected to be broken down and processed or reconstructed into a format that closely resem-

Table 11. Major benefits and limitations of CBCT imaging in the OMF region.

Benefits
- 3D dataset
- real-size data
- potential for generating all 2D images (e.g. orthopantomogram, lateral cephalogram, TMJ)
- potential for vertical scanning in a natural seated position
- isotropic voxel size
- high resolution (e.g. bone trabeculae, Periodontal ligament (PDL), root formation)
- lower radiation dose than MSCT
- less disturbance from metal artifacts
- reduced costs compared with MSCT
- easy accessibility
- in-office imaging
- easy handling
- small footprint
- Digital Imaging and Communications in Medicine (DICOM) compatible
- user-friendly post-processing and viewing software
- energy saving compared with MSCT

Limitations
- low contrast range (dependent on the type of X-ray detector)
- limited detector size causes limited field of view and limited scanned volume
- limited inner soft tissue information
- increased noise from scatter radiation and concomitant loss of contrast resolution
- movement artefacts affecting the whole dataset
- truncation artifacts (caused by the fact that projections acquired with region of interest selection do not contain the entire object)
- can not be used for estimation of Hounsfield units (HU)

bles that produced by other imaging modalities such as MSCT. CBCT imaging will become the imaging acquisition method of choice in the OMF region, but there are some important limitations (Table 11) and concerns. Owing to the relatively small detector size, the field of view and scanned volume are limited. This is the reason why the ideal CBCT scanner for orthodontics and orthognathic surgery is not commercially available. Another disadvantage is that CBCT can not be used for the estimation of HU[162]. The most important disadvantage of CBCT imaging is the low contrast resolution and limited capability of visualising the internal soft tissues. CBCT should not be used as a single imaging modality in polytrauma patients because intracerebral pathology could easily be missed. The easy accessibility and easy handling of dedicated CBCT scanners raise some important concerns because it has caused a major shift in the user group of highly sophisticated 3D CT imaging. Most purchasers of CBCT OMF scanners are specialist dentists and maxillofacial clinicians[64], instead of radiologists, which is the case with MSCT scanners. This trend is not expected to change. The errors and confusion found in the clinical literature on CBCT imaging can be partially attributed to the limited technical knowledge about medical imaging devices of this new user group. A minimum set of CBCT device-related parameters for dedicated OMF scanners (Table 10) was required. This shift in users could lead to important medico-legal consequences. Sophisticated CBCT imaging is performed routinely in many cases by clinicians lacking sufficient anatomical knowledge and experience to interpret the scanned data. Nair[114] pointed this out in a case report of an intracranial aneurysm that was visible on a MSCT study for the assessment of an odontogenic keratocyst. CBCT imaging will improve patient care, but users have to be aware of their responsibility to interpret the data thoroughly. The number of indications in the OMF and non-OMF field are increasing and this has resulted in the need for central-based and multi-speciality accessible CBCT units. The CBCT apparatus should be installed in close collaboration with radiologists.

The increasing popularity of CBCT has resulted in numerous presentations at conferences, dozens of manufacturers' brochures and published papers resulting in an uncontrolled and non evidence-based exchange of radiation dose values.

In conclusion, the results of this review showed that there is a major inconsistency in the reported terminology for CBCT properties and settings and that there is a lack of evidence-based data on the radiation dose for CBCT imaging. Based on the results of this study, a minimal set of CBCT device-related parameters for dedicated OMF scanners is proposed as a guideline for future studies.

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