

**MARGARETE B
MCGUIGAN¹
HENRY F DUNCAN²
KEITH HORNER³**

¹ Division of Oral and Maxillo-facial Surgery, Medicine, Pathology & Radiology, Dublin Dental University Hospital, Trinity College Dublin, Lincoln Place, Dublin 2, Ireland

² Division of Restorative Dentistry & Periodontology, Dublin Dental University Hospital, Trinity College Dublin, Lincoln Place, Dublin 2, Ireland

³ School of Dentistry, University of Manchester, UK

CORRESPONDENCE

MB McGuigan
Dublin Dental University
Hospital
Trinity College Dublin
University of Dublin
Lincoln Place
Dublin 2
Ireland
Tel. +353 (1) 6127356
Fax +353 (1) 6127297
E-mail: Margarete.McGuigan@dental.tcd.ie

SWISS DENTAL JOURNAL SSO 128:
297–316 (2018)
Accepted for publication:
30 August 2017

An analysis of effective dose optimization and its impact on image quality and diagnostic efficacy relating to dental cone beam computed tomography (CBCT)

KEYWORDS

CBCT
Dose
Optimization
Image Quality
Diagnostic Efficacy

SUMMARY

The potential of high resolution, three-dimensional (3D) images which overcome limitations such as superimposition and anatomical noise of two-dimensional (2D) conventional imaging, has made cone beam computed tomography (CBCT) an increasingly popular imaging modality in many dental applications. It is in light of the increasingly prevalent use of CBCT, particularly in a primary dental care setting, that the goal of this review is to investigate what evidence-based guidance is available to the clinician to justify and reduce radiation risk of this higher dose imaging modality while maintaining diagnostically acceptable images. To this end, the literature on radiation dose and related patient risk was comprehensively investigated, before an analysis of the ways in which dose can be optimized and the implications that optimization has on image quality was discussed. Finally, although it is accepted that CBCT

has the potential to improve diagnosis, it is uncertain if its use has positive ramifications on issues of diagnostic efficacy, including clinical decision-making and patient outcome. In order to investigate these issues, the levels of evidence of the existing studies and their validity were assessed. On review of the available literature, it is evident that there is limited practical advice available to dentists regarding dose optimization and any existing protocols may not be readily transferable to every CBCT machine, the manufacturers' role is not often conducive to dose limitation and that the bulk of evidence is at lower levels of evidence. Furthermore, there is minimal supporting evidence to suggest an impact of CBCT on diagnostic thinking and consequent choice of treatment and no evidence of a positive effect of CBCT on patient outcome.

Introduction

Since its introduction in the 19th century, dentomaxillofacial radiology (DMFR) has relied on two-dimensional (2D) imaging, with more recent advancements in radiographic film and digital radiography offering lower doses and faster image production. Conventional 2D radiographs, however, are limited by superimposition, distortion, magnification and misrepresentation of structures (SCARFE & FARMAN 2008) with planar 2D interpretation of the three-dimensional (3D) maxillofacial anatomy creating a superimposed image, which prevents optimal visualization due to overlaying structures (KILJUNEN ET AL. 2015). The introduction in medicine of computed tomography, later followed by cone beam computed tomography (CBCT) (ROBB 1982), heralded the clinical progression from 2D to 3D images generated by computer-enabled reconstruction of the acquired data.

Dental CBCT was introduced commercially in Europe in 1999 (MOZZO ET AL. 1998; ARAI ET AL. 1999) and has since its inception become an increasingly popular imaging modality with a recent report indicating that there are at least 47 different devices (from 20 companies) commercially available in Europe (NEMTOI ET AL. 2013). Rapid advances in detector technology and computer software systems able to handle large volumes of data has propelled the evolution from initial basic prototypes into faster, more sophisticated imaging tools targeted at specific clinical applications (e.g. small volume scanners used in endodontics: Accuitomo 3D; J. Morita Corporation, Kyoto, Japan). CBCT certainly offers a significant benefit over conventional CT imaging by allowing high resolution 3D visualization of the maxillofacial skeleton with adjustable field of views (FOV) sizes and concomitant reduction in patient dose (SCHULZE ET AL. 2004). This 3D visualization offers a wide range of potential applications within dentistry, primarily aimed at examination of the hard tissues as well as the various sinuses and air cavities of the maxillofacial region (DE VOS ET AL. 2008); however, CBCT appears to be of limited value for soft tissue evaluation due to limited low-contrast resolution (SCARFE & FARMAN 2008). Common dental applications include implant planning, maxillofacial surgery, endodontics and orthodontics (ALAMRI ET AL. 2012); but use must be tempered by the understanding that the effective dose of CBCT is significantly higher than traditional intraoral periapical radiography (IOPA) and panoramic radiography (ROBERTS ET AL. 2009). CBCT is also limited by a relatively large degree of noise and artefacts on imaging of high density tissues and metal objects due to scatter, beam hardening and photon starvation (SCHULZE ET AL. 2011). Given the explosion of higher-dose CBCT imaging in dentistry there is certainly an evolving need for robust, evidence-based directives and guidelines on selection criteria and specific dose optimization protocols in key procedures (HORN ET AL. 2013, 2015). The widespread and increasing use of CBCT in dental practice (BERG ET AL. 2014; DÖLEKOĞLU ET AL. 2011; HOL ET AL. 2015) has raised other concerns, with a shift in reporting responsibilities from radiologists to dentists who may not be appropriately trained to interpret all the structures visible on the CBCT scan (PARASHAR ET AL. 2012). As a result, the European Academy of DMFR (EADMFR) has highlighted the lack of dental undergraduate (and perhaps postgraduate) training in this novel evolving technology and has recommended appropriate training in justification, acquisition and interpretation of CBCT imaging (BROWN ET AL. 2014).

CBCT offers clear advantages in 3D visualization and diagnostic accuracy (PATEL ET AL. 2009; MATZEN ET AL. 2013), which are reflected in guidelines advocating its use in specific clinical ap-

plications (EUROPEAN COMMISSION 2012; ESE 2014). Notably, questions remain as to what quantifiable impact 3D imaging has in modifying diagnosis, treatment planning and outcome when compared with conventional radiography. As health care professionals, we must consider if the benefit of CBCT imaging outweighs the associated radiation risks for each individual patient.

Consequently, the aim of this review is to understand radiation risk which involves quantification of dose and an appreciation of dosimetry techniques and their limitations. Reduction of this risk through processes of justification and optimization will be addressed. Specifically, the parameters that can influence CBCT dose will be explored in conjunction with measures and protocols to aid the operator in achieving dose optimization while investigating what impact this has on image quality for a range of diagnostic tasks. Finally, the impact of CBCT on decision-making and treatment outcome will be accessed and gaps in our knowledge highlighted.

Materials and Methods

A comprehensive MEDLINE search up to May 2017 was conducted using various medical subject headings (MeSH) in combination with “and” or “or”. The major MeSH terms searched were “Radiography, Dental”, “Tomography, X-Ray”, “Diagnostic Imaging” and “Radiographic Image Enhancement” in combination with a series of related subheadings. In addition, the following terms were added “optimization” and “CBCT”. Bibliographies of all relevant papers and previous review articles were hand-searched. Any relevant work published in the English language and presenting pertinent information related to this review was considered for inclusion. Titles were generally excluded if they were conference reports or if aspects of CBCT were discussed that were not the subject of the current review.

Review

Optimization in CBCT involves quantification of the radiation dose and risk for patients, while assessing the impact on image quality for specific diagnostic tasks. In order to fully consider CBCT optimization, this review will analyse the literature on dose and risk as well as the impact of optimization on image quality and diagnostic efficacy of CBCT.

Radiation Damage and Protection

Each radiological exposure involves interaction of body tissues with ionizing radiation and therefore carries the potential of permanent alteration in cellular DNA with the ultimate risk of latent tumour formation and hereditary effects. This chance happening is described as a stochastic effect, where the magnitude of risk is believed to be proportional to the radiation dose; notably there is no threshold dose below which these effects will not occur (IRCP 2007). Furthermore, risk is sex and age dependent, being greatest for children (10-year-old 3× higher risk than 30-year-old) and up to 40% more for females than males (IRCP 1990; EUROPEAN COMMISSION 2012).

Practitioners should be aware of the potential effects of ionizing radiation and understand the increased doses attributable to CBCT imaging, this reinforcing the importance of strict adherence to the IRCP principles of justification and optimization (IRCP 2007). Indeed, the preliminary process of justification can be the most effective means of dose reduction particularly for young children and adolescents. Guidance documents and position statements provide a framework for selection criteria to ensure CBCT scans are prescribed appropriately, ensuring a net poten-

tial benefit to the patient. Therefore, in general, guidelines do not advocate CBCT as a routine imaging tool but only when an alternative reduced-dose imaging technique is diagnostically insufficient (HORNER ET AL. 2009; EUROPEAN COMMISSION 2012; FGDP [UK] 2013; ESE 2014; SADMFR 2015 [DULA ET AL. 2015]); however, routine use of CBCT has been recommended by some (DRAGO & CARPENTIERI 2011; NOFFKE ET AL. 2011) but not all groups in implant dentistry. Valid guideline documents should be extracted from the evidence base rather than relying solely on expert opinion and general consensus; however, a recent review (HORNER ET AL. 2015) identified only two evidence-based guidance documents at the time of publication (EUROPEAN COMMISSION 2012; AWMF 2013). This review (HORNER ET AL. 2015) highlights the need for more rigorous and consistent reporting of guidelines, free of potential bias, facilitated by the use of the AGREE 11 (Appraisal of Guidelines for Research & Evaluation 11) instrument. That said, it is recognized that evidence-based guidelines can only reflect the validity of the research that exists. The inherent difficulties of achieving studies at higher hierarchical levels of diagnostic efficacy are discussed subsequently.

Optimization is defined as maintaining doses at levels which are “as low as reasonably achievable” (ALARA), while ensuring that images are still of diagnostic quality (IRCP 2007). Broad guideline documents serve to direct the practitioner in achieving this goal of minimizing patient exposure while achieving the diagnostic information required. Optimization involves a range of factors, from maintenance and selection of equipment most suited to clinical/imaging needs of patient base, selection of the appropriate exposure parameters (Tab. I), limitation of the exposed volume to use of shielding devices and establishing a dose reference level (DRL) (EUROPEAN COMMISSION 2012; HPA 2010). The inherent difficulty of creating a standardized optimization protocol in CBCT imaging relates to the range of clinical protocols and diversity of available CBCT systems. The clinician’s expectation of high resolution and “visually pleasing” CBCT images, perhaps without due consideration of dose implications, has prompted the adoption of a modification of the ALARA principle. The concept of “as low as diagnostically acceptable” (ALADA) acknowledges the link between dose and image quality and encourages the minimum exposure possible for the specific diagnostic task (WHITE ET AL. 2014). The ALADA principle evolved from the drive to increase radiation protection in paediatric populations associated with the increased awareness of their sensitivity to diagnostic radiation (THEODORAKOU ET AL. 2012; PAUWELS ET AL. 2014A; WHITE ET AL. 2014; HIDALGO RIVAS ET AL. 2015; HALL & BRENNER 2008).

What Do We Understand by Patient Dose?

Patient dose monitoring is an essential part of quality assurance (QA) to ensure doses are kept as low as reasonably achievable and allow comparison to DRLs (EUROPEAN COMMISSION 2004). DRLs do not indicate the desired dose level for a specific diagnostic task but instead define a reference dose or threshold above which operators should investigate the potential for dose reduction measures (YU ET AL. 2009). Dosimetry is also essential to study the radiation-induced risk of different types of diagnostic imaging examinations enabling comparison of imaging modalities/devices which can influence directives on justification and dose reduction strategies.

Absorbed dose (D_T) describes the amount of energy absorbed from the radiation beam per unit mass at a site of interest. The SI unit for this is the gray (Gy) representing one joule per kilogramme but the milligray (mGy) is more appropriate in the context of diagnostic imaging (WHITE & PHAROAH 2013). Although useful for quality control purposes (IRCP 2007), radiation absorbed dose gives no indication of stochastic risk. A complicating factor when considering “dose” of radiation is that different types of radiation have different biological effectiveness, in terms of their potential to cause damage. Particulate radiation (high-energy protons, neutrons, alpha particles) cause greater damage than X-rays. Thus, an absorbed dose of 1 mGy from X-rays would give less damage to tissues than 1 mGy from high-energy proton radiation. The differing radiobiological effectiveness of different types of radiation is taken into account by attributing a radiation weighting factor (W_R) to the absorbed dose, resulting in the concept of equivalent dose (H_T), which can be calculated as: $D_T \times W_R$. Fortunately, the W_R of X-rays is 1, but the SI unit of equivalent dose is changed from the gray to the sievert (Sv).

Effective dose (E) (recommended by The International Commission on Radiological Protection [ICRP]) is a more relevant index when considering patient dose. It enables a measure of radiation risk from different exposures of ionizing radiation to various body tissues/organs which exhibit a range of radiosensitivities. Specifically, it is calculated as a product of the equivalent doses to the irradiated tissues and the tissue weighting factor (W_T) (which reflects the degree of sensitivity of each of the tissues to radiation and relative contribution to overall risk). These weighted doses are then summed to deliver the effective dose, which is typically expressed in millisieverts (mSv) or microsieverts (μ Sv). $E = \sum W_T \times H_T$. Importantly, effective dose allows an approximate comparison of radiation-induced risk among different types of examinations. Thus, it becomes possi-

Tab. I The effects of exposure and image quality parameters on dose and image quality

	Exposure and image parameters				
	↑ kV	↑ mAs	↓ FOV	↓ Voxel size	↑ No of projections
Dose	↑	↑	↓	↑ is device dependent	↑
Spatial resolution	X	X	X	↑	↑
Contrast	↓	X	↑	X	X
Noise	↓	↓	↓	↑	↓
Artefacts	↓ Beam hardening	X	↑ Truncation artefact	X	X

ble to compare the radiation-associated risk of, for example, an intraoral radiograph with a chest radiograph or a CT scan of the abdomen.

The most recent tissue weighting factors are provided by the IRCP (IRCP 2007) which revised the existing figures from 1990 (IRCP 1990). Particularly relevant to dental imaging, new tissue weighting factors for salivary glands, oral mucosa, lymph nodes and brain have been included (EUROPEAN COMMISSION 2012). This updating of tissue weighting factors results in a 10% increase in the weighting ascribed to tissues located in the maxillofacial region. Being a relatively recent imaging modality, most CBCT dosimetry research studies have used the updated tissue weighting factors but along with the variation in CBCT device parameters it is worth considering these issues when comparing dose estimations from different studies.

How is Dose Quantified?

In order to compare radiation risk between different types of examination, effective dose is considered the most appropriate metric. Since effective dose cannot be measured directly in vivo, it is only possible to quantify it in laboratory studies or by computer modelling. Traditionally, ascertaining the dosimetry necessary for the calculation of effective dose involved the use of anthropomorphic phantoms constructed from materials that have comparable X-ray attenuation characteristics to human tissue. Multiple thermoluminescent dosimeters (TLDs) are distributed throughout the phantom (position dependent on tissues to be evaluated) to allow for accurate measurement of absorbed dose. Notably, no standards have been set as to the number or locations of the TLDs, often leading to low reproducibility of this technique (LUDLOW ET AL. 2006, 2015; PAUWELS ET AL. 2012A). This fact, compounded by the use of a range of phantoms have resulted in studies that are not readily comparable and highlights the need for a standardized method of dose measurements to enable comparison between studies (PAUWELS ET AL. 2012A).

Computed dose simulations using virtual phantoms have been developed. These virtual phantoms potentially negate the need for the laborious task of repeated dosimetry on standard adult or paediatric phantoms, which do not allow for consideration of population variation in size (KOIVISTO ET AL. 2012; MORANT ET AL. 2012). This technique allows simulation of the interaction of radiation with matter and provides a quick way of modelling the multitude of potential variations within imaging systems and patients. It has been widely used in radiotherapy dosimetry but has also been used in a small number of dental CBCT studies (STRATIS ET AL. 2016; EZELDEEN ET AL. 2017). Appraisal of the use of virtual phantoms with Monte Carlo simulation of exposure as a dependable replacement for anthropomorphic phantoms suggests that further development of virtual phantoms is necessary (ZHANG ET AL. 2013).

Neither laboratory studies using phantoms nor complex computer modelling has direct use in clinical situations. For measuring dose in clinical facilities, particularly for dose audits, alternative measures are needed from which effective dose can be estimated. In the context of dental CBCT, examples of these include dose area product (DAP), also known as kerma area product (KAP). This is a simple, less laborious technique for indirectly estimating effective dose. DAP is defined as the air collision kerma integrated over the beam area. It can be measured using a DAP meter (calibrated ionization chamber that measures dose and beam size at a fixed point). Additionally, DAP

can be available via machine output data (determined computationally, based on the X-ray tube output and field size settings), however, these data can be unreliable and calibration is required (AL-OKSHI ET AL. 2017). Measured DAP values can then be converted to effective dose using conversion factors (KIM ET AL. 2014). There are conflicting opinions as to the accuracy of this dose index in the calculation of effective dose. DAP has been recommended for establishing achievable doses and, possibly, diagnostic reference levels and is described as relating “reasonably well” with effective dose (HOLROYD & WALKER 2010; EUROPEAN COMMISSION 2012). However, the central point of the scan is not always in the centre of the clinical area of interest and patient dose measurements could be either underestimated or overestimated. It has been demonstrated that within a small field of view (FOV), although effective doses exhibited a three-fold change over three separate locations, DAP remained unchanged (LUDLOW 2009). Additionally, an average of 35% absolute error in calculation of the effective dose resulted when using DAP, even when using conversion factors specific for FOV size, arch location and patient type (KIM ET AL. 2014). Furthermore, it was concluded that since imaging factors (FOV size and positioning) govern the actual distribution of dose throughout the patient, generally it would not be possible to link DAP values to patient effective doses (PAUWELS ET AL. 2012A). Accepting its limitations (LARSSON ET AL. 1996; LUDLOW & IVANOVIC 2008) and being aware that its precision as a measure of risk is questionable (LUDLOW ET AL. 2015), it was reported that DAP could be used to assess dose reduction strategies and compare the results from different CBCT units (LOFTHAG-HANSEN 2010; GOULSTON ET AL. 2016).

Interestingly, use of dose height product (DHP) in place of area resulted in statistically improved accuracy in the estimation of effective dose, with a reduction in absolute error to 19% from 35% evidenced with DAP (LUDLOW ET AL. 2015). Ludlow theorized that DHP may correlate more with effective dose than DAP due to the nature of the vertical distribution of radiosensitive organs. Therefore, an increase in height of the FOV results in new and potentially radiosensitive tissues being brought into the area of direct exposure, while an increase in beam width merely results in an increased dose to tissues that are already being exposed. It was concluded that the use of DHP as a means of estimating effective dose merits further investigation (LUDLOW ET AL. 2015). CT dose index volume (CDTI) is the international assessment metric used to measure the radiation output of CT scanners. Studies have revealed that CDTI measurement methodology does not accommodate the cone shaped beam of CBCT and the larger FOVs (MORI ET AL. 2005).

It has been established that owing to its unique exposure geometry (eliciting a dose distribution which can be asymmetrical and exhibits a strong dose gradient outside the primary beam), CBCT requires a specific dose index that copes with differences in FOV, diameter, positioning and varying degrees of rotation arc (PAUWELS ET AL. 2012C). Alternative dose indices have been explored by the SEDENTEXCT team but further work is necessary to establish if such indices are appropriate for establishing DRLs (EUROPEAN COMMISSION 2012).

What Are the Reported CBCT Doses and How Does CBCT Compare to Conventional Radiography?

The effective dose ranges quoted for CBCT reflect the range of devices and imaging protocols (collimation of the cone beam, exposure factors, image quality parameters), in addition to the

location of the radiation field with respect to the radiosensitive organs, which leads to a considerable difference in absorbed dose for all organs in the head and neck region (PAUWELS ET AL. 2012A; THEODORAKOU ET AL. 2012; BORNSTEIN ET AL. 2014; PAUWELS ET AL. 2014A; LUDLOW ET AL. 2015). As a result of this diversity between devices, it is not possible in the field of CBCT to establish a single average effective dose when making comparisons to conventional 2D radiography and multi-slice CT (MSCT) (PAUWELS ET AL. 2012A). Effective dose for CBCT has been quoted in tens to several hundred μSv , demonstrating a twenty-fold range (PAUWELS ET AL. 2012A; EUROPEAN COMMISSION 2012; PAUWELS ET AL. 2014A; LUDLOW ET AL. 2015). If effective dose calculations are categorised by FOV size (see optimization section), dose ranges have been demonstrated using a broad selection of devices such as: small FOV: 19–44 μSv , medium FOV: 28–265 μSv and large FOV: 68–368 μSv (PAUWELS ET AL. 2012). These figures clearly demonstrate the impact of FOV size of which FOV height is believed to be the key determinant of effective dose (PAUWELS ET AL. 2014A). An intraoral periapical radiograph (IOPA) effective dose is quoted as less than 1.5 μSv when all parameters are fully optimized (LUDLOW ET AL. 2008). Reported effective dose ranges for panoramic radiography are 2.7–24.3 μSv and less than 6 μSv for cephalometric radiography (EUROPEAN COMMISSION 2012), this confirming the fact that radiation dose and risk is considerably greater for CBCT than conventional radiography. It is generally accepted that effective doses for CBCT are well below those for common MSCT protocols, with a range of dose being reported as 280–1,410 μSv (EUROPEAN COMMISSION 2012). However, CBCT images with a large FOV and high exposure factors can have comparable dose ranges with low-dose MSCT protocols (LOUBELE ET AL. 2009; SUOMALAINEN ET AL. 2009; KYRIACAOU ET AL. 2011).

The effective dose from a dental CBCT exposure is mainly defined by the absorbed dose of the remainder organs (38%), salivary glands (25%), thyroid gland (19%) and red bone marrow (14%). If the effective dose of a small FOV upper anterior scan (19 μSv) is compared with a lower molar scan (40 μSv), the observed difference in effective dose can be attributed to the increased absorbed dose, particularly of the salivary glands and thyroid gland associated with a mandibular scan (PAUWELS ET AL. 2012A). This variation clearly demonstrates the impact of FOV position relative to the radiosensitive organs on patient dose.

When appropriate child settings are selected, effective doses for children and adolescents (measured in paediatric and adolescent phantoms) have been reported as similar to effective doses measured in adult phantoms; the lowest effective doses reported resulted from small FOV and “small-patient” settings (THEODORAKOU ET AL. 2012). In the paediatric phantom, equal contributions to effective dose come from the remainder organs, salivary and thyroid glands. Other studies have reported that, where imaging protocols remained constant (adult setting), the highest absorbed dose was measured in all locations in the small-child phantom and the lowest in the adult phantom which attenuated more radiation due to its increased diameter (AL NAJJAR ET AL. 2013; CHOI & FORD 2015). An increasing number of paediatric CBCT scans are being performed with indications including impacted teeth, orthodontics and dento-maxillofacial development, highlighting the need for appropriate justification and dedicated paediatric protocols optimized for the imaging task (CHOI & FORD 2015; HIDALGO RIVAS ET AL. 2015).

Risk Considerations Related to CBCT

Effective dose was developed for use in radiation protection to provide a measure of overall risk of stochastic effects from diagnostic radiation exposure. However, with regards to CBCT imaging, it is generally measured in a standard phantom, estimating risk for an average-sized adult reference patient. This does not reflect the risk of the individual patient who varies in size and mass with a concomitant variation in dose (MARINE ET AL. 2010; CASSOLA ET AL. 2011). This has implications particularly for children, being physically smaller, with more tissue (e.g. brain and thyroid now closer to dental area) in the primary beam and subject to scatter radiation; therefore, absorbed dose to the head and neck regions will be higher if appropriate “child settings” are **not** used (BORISIVA ET AL. 2008; THEODORAKOU ET AL. 2012; AL NAJJAR ET AL. 2013). Furthermore, this increased risk is compounded by age (owing to their larger proportion of dividing cells and a longer remaining lifespan to express stochastic effects) and gender sensitivity (female risk > male risk) to potential stochastic effects from radiation (IRCP 1990). It was concluded that, since effective dose is not individual-specific, it is not a suitable quantity for individual patient risk estimation but is considered a useful indicator of relative risk when comparing a range of examination protocols or differing imaging modalities (LUDLOW ET AL. 2015). Interestingly, a method to estimate patient-specific dose and cancer risk from CT examinations has been developed by combining a validated Monte Carlo programme with patient-specific anatomical models (LI ET AL. 2011).

There is continuing debate about the level of risk associated with diagnostic imaging and the validity of the linear-no-threshold model (LNT) of extrapolating cancer risk from higher doses to lower levels of exposure (IRCP 2007; TUBIANA ET AL. 2009). The uncertainty lies with the inherent limitations associated with the studies available for risk analysis of low doses (PAUWELS ET AL. 2014A). Such data includes the life-span study of atomic bomb survivors, which serves as a model for determining cancer risk for low doses (PRESTON ET AL. 2007). Additionally, epidemiological studies on the cancer risk of CT scan exposures to the maxillofacial region suggest that increased risks associated with doses applicable to CT are not hypothetical and are independent of extrapolations and modelling. These studies have demonstrated a significant increase in brain cancer and leukaemia among the scanned subjects, the increased incidence being associated with increasing dose and young age at the time of exposure (PEARCE ET AL. 2012; MATTHEWS ET AL. 2013). These studies support the LNT hypothesis of a proportional increase in cancer risk and heritable defects concomitant with any exposure of radiation above zero. Of note, other dose risk models exist which are diverse from the LNT hypothesis (e.g. radiation hormesis and supralinear models) while others adhere to the principles of the LNT hypotheses while involving a dose and dose-rate effectiveness factor (DDREF) to compensate for the potentially lower biological effectiveness of low doses. However, current literature appears to support the LNT hypothesis (IRCP 2007; BARRET ET AL. 2015).

When considering risk specifically associated with CBCT, it has been estimated that the lifetime attributable risk (LAR) for cancer induction is between 2.7 and 9.8 per million examinations (PAUWELS ET AL. 2014A). Children exhibit the highest cancer risk in this spectrum due to their increased radiosensitivity, which highlights the importance of an understanding of this increased risk by operators and referrers and implementation

of a more rigorous application of the ALARA principle (HORNER ET AL. 2009). These LAR figures were calculated by applying established correlation factors (PAUWELS 2012A, 2012B) to measured skin doses on patients receiving CBCT scans to estimate patient organ dose. Individual effective dose was then calculated using tissue weighting factors (IRCP 2007). Finally, lifetime attributable cancer risk was calculated from gender- and age-specific risk factors reported in the Biological Effects of Ionizing Radiation (BEIR) VII report (NATIONAL RESEARCH COUNCIL OF THE NATIONAL ACADEMIES 2006).

Technical and Imaging Parameters that Influence Dose Optimization

The technical principles and details of CBCT design have been reviewed in detail (SCARFE & FARMAN 2008; NEMTOI ET AL. 2013; KILJUNEN ET AL. 2015; PAUWELS ET AL. 2015A). The aim of the current review is to analyse the manner in which technical specifications, optimum selection of exposure and image quality parameters can minimize radiation and risk to the patient, while maintaining image quality and diagnostic accuracy. This aim adheres to the principle of optimization stipulated by the IRCP (IRCP 2007).

CBCT imaging is accomplished using a rotating gantry (similar to a panoramic system) to which an X-ray source and opposing detector are fixed in a C-shaped arm arrangement (PAUWELS ET AL. 2015A). Scanning can be performed in a standing (most common but susceptible to patient movement), sitting or supine position (space-demanding) according to device design or patient requirements. Each unit has a device specific stabilization method to minimise patient motion which can degrade image quality (SPIN-NETO ET AL. 2016; DONALDSON ET AL. 2015). The fundamental principle of X-ray production is similar for two- and three-dimensional imaging modalities, the X-ray tubes differing mainly in the size of the exit window (i.e. collimation), the range of exposure factors and the amount of beam filtration (PAUWELS ET AL. 2015A). Dental CBCT utilizes a cone- or pyramid-shaped X-ray beam, which is directed at the required FOV, the X-ray source and detector rotating around a rotation fulcrum fixed within the centre of the region of interest. Rotation times vary most commonly between 10 and 40 seconds during which the X-ray exposures (at certain degree intervals) result in several hundred 2D projections (raw data) being acquired by the detector. These images have been described as similar to lateral and posterior-anterior cephalometric images, each slightly offset from the other (SCARFE & FARMAN 2008). Only one rotation sequence is required to acquire sufficient data for image reconstruction as the beam incorporates the entire FOV. This differs from medical CT which uses a fan shaped beam in a helical movement and acquires only individual slices of the FOV at a time.

Exposure Settings

The dose associated with each CBCT scan is affected by exposure parameters; tube operating potential ("voltage"), measured in kilovolt (kV), and tube current exposure time product, measured in milliamperere (mA). These parameters are initially determined by the manufacturer, perhaps with an emphasis on delivering images of high quality rather than dose optimization. Some CBCT models have preset exposure settings for differing clinical applications (e.g. endodontic mode) and for patients of different sizes thus enabling a degree of dose and image optimization. Other devices enable the operator to select the kV, mA

and exposure time within a specified range allowing the user the possibility of reducing dose for a smaller patient/child or for a particular diagnostic task. This necessitates operator knowledge and experience and demands evidence-based guidance regarding the impact of exposure parameters on image quality for specific diagnostic tasks. Collaboration of the clinician with a medical physicist and engineer can facilitate further optimization. The use of automatic exposure control (AEC – used in CT imaging) has been introduced in CBCT imaging. The aim of AEC is to automatically modify the tube current to accommodate attenuation differences due to patient size, shape and anatomy, for example when the mA values are varied depending on the density distribution of a scout image (KALENDER ET AL. 1999). In CT, AEC has been found to lead to a significant dose reduction and could negate the need to manually adapt the kV and mA according to patient size (PAPADAKIS ET AL. 2008).

Current Exposure Time Product (mA)

For the CBCT devices available, tube current ranges from 1 to 32 mA (KILJUNEN ET AL. 2015). Both the tube current and exposure time (seconds) determines the quantity of X-ray photons produced which reach the detector. When other exposure factors are kept constant, a linear relationship exists between current exposure time product (mA) and patient dose i.e. increasing mA values cause a proportional increase in dose. With regards to image quality, an increased mA value decreases image noise by increasing signal at the detector but since the beam penetration remains the same, contrast is unaffected.

Tube Voltage

Typical tube voltages in existing CBCT scanners vary most commonly between 60 and 90 kV (full range 40–120 kV) (KILJUNEN ET AL. 2015). As tube voltage increases, the mean energy/penetrating power but also the quantity of the photons in an X-ray beam increases and, overall, radiation dose is increased (other factors being constant). However, unlike current exposure time product the relationship between tube voltage and dose is not linear. Higher kV values increase the detector signal due to the increased photon count and a decreased absorption ratio. In respect to image quality, at a higher kV value the difference in X-ray attenuation between tissues of differing density is decreased, which can result in a decreased image contrast (Tab. II). Conversely, a lower kV value can lead to increased image contrast with regards to the hard tissue of the maxillofacial region (DRAGE ET AL. 2010). However, this dynamic of increased contrast at lower beam energies is not fully translatable to CBCT due to the complementary information of projectional data from many angles (PAUWELS ET AL. 2014B). Nevertheless, there is the potential to decrease the voltage and thus dose while maintaining image contrast, which is especially pertinent for smaller patients/children where less penetrating X-rays (80 kV or less) are required (YU ET AL. 2009). A reduced kV value is associated with increased noise; however, the compensating effect of better contrast maintains the contrast-to-noise ratio (CNR) (KARMAZYN ET AL. 2013). With the greater attenuation associated with larger patients and accompanying increase in noise, a greater tube voltage has been recommended (SEIGEL ET AL. 2004).

Certainly, optimization by kV and mA reduction below the manufacturer's recommendations has been investigated with maintenance of image quality (objective and subjective), facilitating diagnostic accuracy and significant dose reductions

Tab. II Image quality characteristics			
Image quality characteristic	Definition	Determining factors	Characterized by:
Spatial resolution	Ability to discriminate small structures in an image. Especially relevant where depiction of fine detail is critical for diagnosis. Spatial resolution is approx. one order of magnitude lower than that of PR (periapical radiography).	Nominal detector pixel size, fill factor, detector motion blur, grey-level resolution, reconstruction technique applied, patient movement, scatter, imaging parameters (see Tab. I)	Traditionally, assessed visually in line-pairs per millimeter ($lp\ mm^{-1}$). Considering movement and scatter effects, a realistic spatial resolution of $\geq 1\ lp\ mm^{-1}$ has been suggested (HORNER ET AL. 2015) Automated assessment: modulation transfer function (MTF) – the ability of the system to transfer a signal of a given spatial frequency. It is a metric for the objective measurement of spatial resolution in X-ray-based tomographic modalities
Contrast	Ability to distinguish tissues or materials of differing densities. Contrast resolution of CBCT is limited by scattered radiation and FPD-related artefacts (saturation, dark current and bad pixels). CBCT soft tissue contrast is lower than MDCT.	Dynamic range of detector, bit depth of reconstructed images, exposure factors (see Tab. I)	Contrast to noise ratio (CNR) – combines contrast and noise and is a metric of imaging performance with respect to large structures of varying attenuation.
Noise	Scattered radiation that is recorded by pixels on the detector contributes to image degradation. Scatter \propto total mass of tissue contained within the primary X-ray beam, increasing with object thickness and field size. Additional sources: Quantum noise: statistical variations in the homogeneity of the incident X-ray beam. Electronic noise: caused by the conversion and transmission of the detector signal.	Exhibits an interdependent relationship with spatial resolution i.e. factors that improve one (e.g. voxel size) degrades the other.	CNR: can be enhanced by changing some parameters during scanning procedure such as the FOV, mA, kV and projection number. However, high-density materials such as metals can cause beam hardening and streak artefact which leads to a decrease in the CNR.
Artefacts	Inherent artefacts: – Scatter – Partial volume averaging – Cone-beam effect Procedure-related artefacts: – Undersampling Scanner related artefacts: – Circular artefact Introduced artefacts: – Cupping and extinction artefact – Patient motion artefact	– Capture of scattered photons. – Selected voxel size is larger than size of object being imaged. – Divergence of the X-ray beam means that structures at the top or bottom of the image field or only exposed when X-ray source is on the opposite side of the patient. – Too few basis projections or incomplete scanning trajectory. – Imperfections in scanner detection or poor calibration. – Both of these artefacts are a result of beam hardening (absorption of lower-energy photons in preference to higher-energy photons as the beam passes through a given material and is more pronounced for denser materials i.e. metal) – Patient motion causes misregistration of data, the smaller the voxel size the more marked the effect of patient movement.	– Increased noise, streak artefacts. – “Step appearance” in image or homogeneity of pixel intensity. – Streaking artifacts and greater peripheral noise. – Misregistration of data by reconstruction software (aliasing) resulting in increased image noise and appearance of fine striations radiating from the edge of image moiré pattern. – Circular or ring streaks. – Distortion of metallic structures due to differential absorption. – Streaks and dark bands between two dense objects. – Double contours in the reconstructed image.

FPD – flat panel detector; MDCT – multi-detector computed tomography

Tab. III Studies demonstrating exposure factor reductions that maintained images of diagnostic quality in a range of diagnostic tasks

Study	Diagnostic task	Exposure factors altered	Reference standard	Dosimetry	Recommendation of low-dose protocol	Principle conclusions
KWONG ET AL. 2008	Diagnostic quality of images assessed via questionnaire	– kV – mA	No standard	Not recorded	Not described	– Images at reduced kV and mA generally maintained DA – High observer variation in quantifying image quality
BROWN ET AL. 2009	Orthodontic linear accuracy (LA) study	Exposure time	Dry human skull measurements	Not recorded	Not described	Reduced exposure time (projections) did not reduce DA
SUR ET AL. 2010	Implant planning, identification of relevant anatomic landmarks	– mA – Exposure time by using 180° and 360° rotations	Reference exposure 80 kVp, 8 mA, 360° rotation	Not recorded	Not described	Reducing rotation at 4 mA provided acceptable image quality, image quality at 2 mA provided acceptable image quality only with 360° scans.
DURACK ET AL. 2011	Detection of simulated external inflammatory resorption (EIR)	Exposure time by using 180° and 360° rotations	Reference exposure 90 kVp/3 mA/17.5 s, 360° rotation	Not recorded	Not described	Reducing rotation from 360° to 180° with small FOV reduced exposure time but not DA
LENNON ET AL. 2011	Detection of simulated periapical bone loss	Exposure time by using 180° and 360° rotations	No standard	Not recorded	Not described	– Reducing rotation from 360° to 180° reduced exposure time but not DA – Wide range of interobserver variation
AL-EKRISH 2012	Implant planning/dimensional accuracy	Exposure time (three different times)	Dry human skull measurements	Not recorded	Not described	Reliability and dimensional accuracy remain the same with the chosen reductions in exposure time.
HASHEM ET AL. 2013	LA of simulated external inflammatory resorption	Exposure time by using 180° and 360° rotations	Dry porcine hemimandible measurements	Not recorded	Not described	Reducing rotation from 360° to 180° produced equally accurate measurements.
WALTRICK ET AL. 2013	Implant planning/LA and visibility of mandibular canal	Exposure time by using 3 different resolution settings	Dry human skull measurements	Not recorded	Not described	All protocols produced an image adequate for measurements and mandibular canal visualization.

MBC – marginal bone crest; CEJ – cementoamel junction; ED – effective dose; TAT – tooth autotransplantation

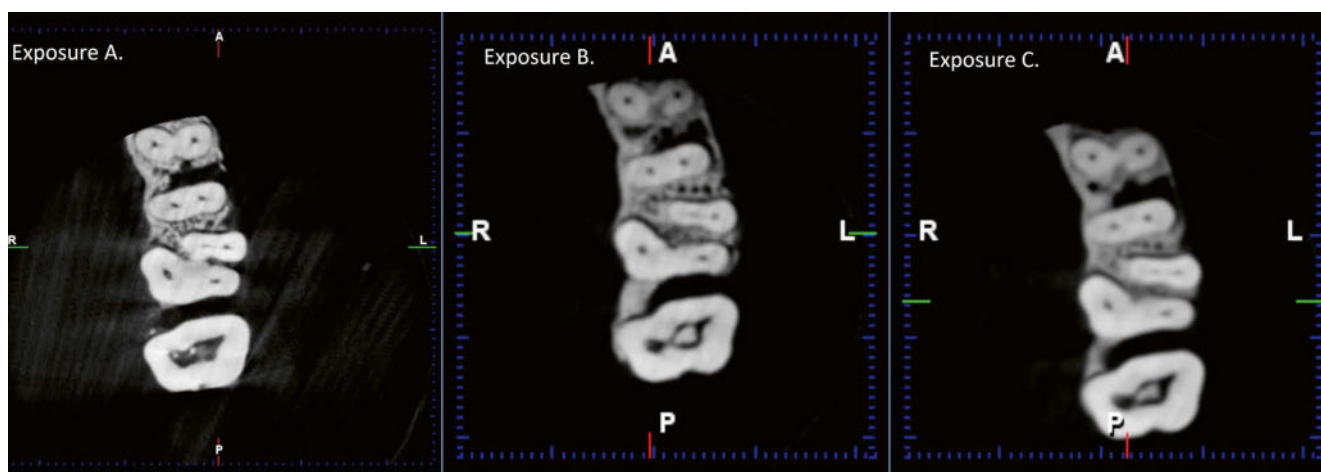


Fig.1 The effect of exposure factors (kV, mA) and choice of exposure parameter (voxel size) on image quality is demonstrated by exposing the 16 region of a dry skull using a ProMax 3D Classic (Planmeca Oy, Finland) CBCT scanner. From exposure A to C, kV, mA values are reduced and voxel size is increased by selecting smaller-patient settings and moving from high-resolution to ultra-low-dose (ULD) settings. Although the image sharpness is reduced, it remains diagnostically acceptable with the identification of the MB2 still possible (exposure C.), illustrating the principle of optimization.

Tab. III Studies demonstrating exposure factor reductions that maintained images of diagnostic quality in a range of diagnostic tasks

continued

Study	Diagnostic task	Exposure factors altered	Reference standard	Dosimetry	Recommendation of low-dose protocol	Principle conclusions
YADAV ET AL. 2015	Detecting arthritic change in the TMJ	Exposure time with 180° and 360° rotations	Dry human skulls with simulated soft tissue and artificial joint lesions	Not recorded	Not described	Images were equally diagnostic at 180° and 360° rotations (other exposure factors remained identical).
HIDALGO RIVAS ET AL. 2015	Evaluation of impacted maxillary canines and possible adjacent resorption in paediatric skull phantom. Objective measure of image quality	– kV – mA	Reference image data sets using highest and lowest exposures possible with device being used	DAP metre	80 kV, 3 mA	Implementation of a low-dose protocol (particular to the single device used in study) could achieve up to a 50% dose reduction while maintaining image quality sufficient for evaluation of impacted maxillary canines. Optimum CNR was achieved at a lower tube voltage than maximum.
AL-OKSHI ET AL. 2017	Assessment of periodontal space at apical third of root, MBC and CEJ. Objective measure of image quality	– kV – mA – Trajectory arc – 180°, 360°	No standard	DAP metre	80 kV/5 mA/360° or 17.5 s	CNR and visualization of periodontal structures were not compromised at this lower-dose protocol. 180° rotation degraded image quality.
EZELDEEN ET AL. 2017	Planning and tooth replica fabrication (TAT) and follow-up on three different CBCT devices	kV, mA and time Altered via selecting a range of predefined protocols (18) on three CBCT machines (FOV alteration necessary pre-/postop)	Reference CBCT scanning protocol validated for accurate tooth and bone segmentation	Monte Carlo dose simulations for three paediatric models	Predefined low-dose protocols specific to device	Use of device-specific predefined low-dose protocols can achieve considerable ED reductions while maintaining image quality for TAT.

MBC – marginal bone crest; CEJ – cementoamel junction; ED – effective dose; TAT – tooth autotransplantation

(Tab. III, Fig. 1). Unfortunately, the effect of changing one or both of the exposure factors is not straightforward. An objective image quality study recommended that a low-dose protocol should constitute reduction of the tube current exposure time product (depending on the clinical application), while keeping the tube voltage constant at 90 kV (highest kV value in device studied) as this achieved the highest CNR at low-dose levels (PAUWELS ET AL. 2015B). The inference of Pauwel's study (2015b) being that the increase in noise for a given mA reduction would be less than that seen with a kV reduction. However, another study (same CBCT scanner used), assessing image quality relating to the anterior maxilla in a paediatric skull phantom, found that dose reductions (50% less than manufacturer's recommendations) could be achieved with a reduction in X-ray tube voltage (80 kV) and indeed for a range of combinations of kV and mA (HIDALGO RIVAS ET AL. 2015). Optimizing kV and mA settings is difficult and involves appropriate balancing, where sufficient image quality is achieved de-

pendent on imaging task at the lowest dose possible and the need for more studies in this area has been highlighted (EUROPEAN COMMISSION 2012).

Field of View

The dimensions of the field of view (FOV) are dependent largely on the size and shape of the detector, the beam projection geometry and the ability to collimate the beam (SCARFE ET AL. 2008). The FOV is either cylindrical or spherical and collimation of the primary X-ray beam using adjustable lead shields limits exposure to the anatomical area of interest, thus avoiding unnecessary exposure. CBCT devices can be categorized according to the dimensions of the FOV. Some devices offer a single fixed FOV, with the majority offering a few pre-set options of FOV, particular to a specific indication. Other devices allow freely adjustable FOVs within certain limitations with another option being the stitching together of adjacent 3D volumes to achieve a larger FOV. The drawback of stitching being that the over-

lapped area is imaged twice, doubling the exposure to such areas. FOVs (described as diameter [D] × height [H] in cm²) can range from small (<10 cm in field height, e.g. D×H: 4×4 cm², suitable for imaging a localized dentoalveolar area [1–3 teeth] and 8 cm×8 cm², suitable for imaging the dentate areas of the maxilla and mandible) to medium (10–15 cm in field height). Large FOVs (>15 cm in field height) are required for full craniofacial imaging (up to dimensions of 26×26 cm²).

Reducing the FOV size (specifically in field height) is the most straightforward method of reducing patient radiation dose and is a key factor in CBCT optimization (DAVIES ET AL. 2012; PAUWELS ET AL. 2012A; THEODORAKOU ET AL. 2012; BORNSTEIN ET AL. 2014; PAUWELS ET AL. 2014A; LUDLOW ET AL. 2015). Nevertheless, with the diversity of devices and scan options, an approximate ten-fold variation in dose for an equivalent FOV was reported between the units studied (BORNSTEIN ET AL. 2014). FOV size and collimation in addition to diagnostic image quality are key determinants in the diagnostic application of a CBCT device (HIRSCH ET AL. 2008; LOUBELE ET AL. 2009). In relation to image quality, an increase in FOV results in a relatively greater amount of scatter reaching the detector and thus is accompanied by a relative increase in noise/artefacts and a reduction in contrast.

Larger FOVs have implications for the thyroid gland, especially for children. This radiosensitive organ has a significant contribution to effective dose (17–20% in adults, 30–37% in children) (IRCP 2007) and can be exposed to scatter (contribution of internal scatter is uncertain) and possibly to the primary beam in dental CBCT. Use of thyroid shields has demonstrated a thyroid dose reduction in children (17–42%) and adults (20–49%) (TSIKLAKIS ET AL. 2005; QU ET AL. 2012; HIDALGO-RIVAS ET AL. 2015). Thyroid shielding is not mandatory in the EU as it was concluded that the thyroid gland is not normally in the primary beam during dental CBCT scans (HPA 2010; EUROPEAN COMMISSION 2012). However, it is advised that a decision should be made locally with the aid of a medical physics expert concerning large FOV scans, if it is likely the thyroid lies in or close to the primary beam. Notably, in the USA, dentists are advised to use thyroid shielding routinely for all dental radiography and for CBCT as long as this does not interfere with the examination (www.thyroid.org, www.imagegently.org). However, if the thyroid shield lies within the X-ray beam, even if outside the displayed FOV, it will attenuate the beam and produce artefacts on CBCT scans. Furthermore, if an AEC is used, at least in theory, a thyroid shield may reduce the dose to the receptor sufficiently to increase automatically the exposure.

Filtration

Filtration serves to limit patient exposure to lower energy photons, which will contribute to skin dose but not to image formation. Therefore, highly filtered X-ray beams have an increased mean energy, reduced entrance exposure and suffer less from beam hardening, but can be associated with loss of contrast (LOFTHAG-HANSEN ET AL. 2008; ROBERTS ET AL. 2009; LUDLOW 2011). CBCT scanners typically utilize aluminium filtration (2.5–12 mm) with some devices using additional copper filtration. Dose reductions associated with additional copper filtration in selected CBCT devices have been reported (LUDLOW & IVANOVIC 2008; QU ET AL. 2010; LUDLOW 2011; KOIVISTO ET AL. 2012). In reality, clinicians using CBCT have no easy means of changing filtration, which would require the input of a medi-

cal physics expert and an equipment engineer. Even then, this would be challenging without cooperation from equipment manufacturers.

Detector

The X-ray detector samples the attenuated beam in its trajectory. The incoming X-ray photons are converted by X-ray detectors to an electrical signal. The majority of modern CBCT scanners utilize indirect flat panel detectors (FPD) consisting of a pixel array of hydrogenated amorphous silicon thin-film transistors (TFT) or complementary metal oxide semiconductors (CMOS). In both cases a layer of scintillator material (gadolinium oxysulfide or caesium oxide) converts X-ray photons to light photons. Subsequently, the light is detected on the photodiodes and read from the entire detector array to compile a raw-data digital image (KILJUNEN ET AL. 2015). FPDs offer higher spatial and contrast resolution, greater dynamic range and reduced peripheral distortion compared with the earlier generation image intensifiers and charged coupled devices (CCD) technology, which have gradually been superseded (BABA ET AL. 2004; NEMTOI ET AL. 2013; PAUWELS ET AL. 2015A). Involvement of a medical physics expert at installation is deemed essential to optimize the detectors parameters with regards to dose and image quality (EUROPEAN COMMISSION 2012).

Image Quality Parameters: Exposure Frequency, Rotation Arc, Number of Projections, Voxel Size

Exposure Frequency: Continuous v Pulsed Exposure

Certain CBCT units utilize continued X-ray exposure; i.e. exposure time equals scan time. However, constant exposure during signal integration contributes to patient dose but not to image formation as most detectors are unable to record X-ray exposure during the acquisition process. To avoid this unnecessary exposure, many CBCT units have a pulsed/intermittent X-ray emission to coincide with detector activation, ensuring that there is no exposure being made between projections. Pulsed-emission systems not only result in a reduced dose but also may exhibit improved spatial resolution owing to a reduced-motion effect (PAUWELS ET AL. 2015A).

Rotation Arc

The rotation angle generally varies between 180° and 360° (CBCT device dependent), the majority of scanners having a single fixed rotation angle with some devices enabling selection of a variable rotation arc according to scan protocol (HORNER ET AL. 2013; NEMTOI ET AL. 2013). A shorter scan arc results in a reduced scan time and hence dose (lower total mA value) with a 180° arc resulting in an approximately 50% dose reduction compared to a 360° arc. Images produced by partial rotation have been associated with increased reconstruction artefacts (SCARFE & FARMAN 2008; BECHARA ET AL. 2013). Additionally, while it would be expected that this reduced mA value would be accompanied by increased noise and reduced image quality, studies demonstrate that for particular diagnostic tasks image quality and diagnostic accuracy can be maintained (LOFTHAG-HANSEN ET AL. 2011; DURACK ET AL. 2011; LENNON ET AL. 2012). This finding implies that manufacturers' recommendations for exposure factors are too high for these tasks.

Number of Projections

The number of acquired projection images ("basis images") during the scan arc movement is determined by the rotation

time, frame rate (number of projection images per second), the completeness of the trajectory arc and the speed of the rotational movement (SCARFE & FARMAN 2008). A greater amount of projection data generally necessitates a longer scan time, with greater potential for patient movement and consequently a higher patient dose. However, enhanced image quality accompanies increased projection data; providing more information to reconstruct the image, allowing for greater spatial and contrast resolution and an increased signal-to-noise ratio and decreased metallic artefacts (PAUWELS ET AL. 2013). Moreover, minimizing the “raw” images (at a level compatible with sufficient image quality) can result in reduced patient dose (via ↓ mA). It has been demonstrated that an increased number of projections does not influence linear accuracy (BROWN ET AL. 2009). Notably, it is reported that increasing exposure does not improve the appearance of metal artefacts sufficiently to justify the increased radiation exposure (PAUWELS ET AL. 2013). Additionally, there are metal artefact reduction techniques that can be employed during reconstruction (VAN GOMPEL ET AL. 2011). Other artefact reducing techniques involve the iterative reconstruction process or using more sophisticated projection and back-projection techniques (WANG ET AL. 1999; DE MAN ET AL. 2004). All these methods, however, require extensive computational power and further work is necessary before they are available in commercial CBCT units (SCHULZE ET AL. 2011).

Voxel Size

Voxels (the individual volume elements) produced in formatting the volumetric data set, dictates the spatial resolution of a CBCT image (SCARFE & FARMAN 2008). Voxel size can be selected on most dental CBCT systems according to the particular diagnostic task. Overall, voxel sizes of CBCT equipment range from 0.075 to 0.6 mm, although individual machines will not normally provide the full range. The smaller the voxel size, the higher the spatial resolution (Fig. 1) and therefore smaller voxel sizes are selected when a high level of detail is required e.g. for endodontic purposes (LIEDKE ET AL. 2009; KAMBOROĞLU & KURSUN 2010; MELO ET AL. 2010; MARET ET AL. 2012). However, voxel dimensions primarily depend on the pixel size on the area detector and smaller pixels capture fewer X-ray photons which result in more image noise. This may require a compensatory increase in radiation dose to achieve a sufficient signal-to-noise ratio to achieve this improved diagnostic image quality (via ↑ mA or basic images). Some devices allow the operator to control exposure factors used with different resolutions, while others automatically dictate exposure factors accompanying particular voxel sizes in order to keep noise relatively constant. Notably, a study reported that the patient dose was doubled on selection of the high resolution from standard on a particular CBCT unit (LUDLOW & WALKER 2013). In the pursuit of dose optimization, the lowest resolution (larger voxel size) option should be selected where the nature of the diagnostic task permits (EUROPEAN COMMISSION 2012). Indeed, the effect of voxel size on diagnostic outcome has not yet been systematically demonstrated (SPIN-NETO ET AL. 2013). From the small numbers of studies systematically reviewed, a trend of increased diagnostic accuracy relating to higher voxel resolutions was evidenced, however, it is not yet possible to suggest general protocols for the different diagnostic tasks and further studies are needed to establish accurate guidelines.

It is apparent from the aforementioned that the image quality (ability of CBCT images to display the required anatomical fea-

tures and/or pathologies) and consequent dose of CBCT imaging is influenced by a number of variables (Tab. I). Such variables include: the individual device (e.g. detector, filtration, FOV capabilities etc.), the exposure parameters (kV, mA) and image quality parameters (voxel size/resolution, basis images [dependent on rotation arc, exposure frequency]). Selection of the optimal combination of scanning parameters to reduce dose can prove a challenge to the operator with very little in the way of practical guidance. While general recommendations on dose optimization exist (HPA 2010; EUROPEAN COMMISSION 2012; AMERICAN DENTAL ASSOCIATION COUNCIL ON SCIENTIFIC AFFAIRS 2012), a recent review highlighted the need for more specific guidance on how optimization can be achieved in practice (GOULSTON ET AL. 2016). Nevertheless, it is accepted that establishment of diagnostic task-specific protocols may prove difficult due to wide range of CBCT devices and capabilities. The development of low-dose protocols in a range of diagnostic applications has gone some way in beginning to achieve optimization (HIDALGO RIVAS ET AL. 2015; AL-OKSHI ET AL. 2017) as could device-specific low-dose preset options (EZELDEEN ET AL. 2017).

Image Quality

In keeping with the ALADA principle, the image quality attained should be sufficient to achieve the specific diagnostic task, but at the minimum exposure possible. The operator must be aware that the acceptable level of image quality and the radiation dose may vary according to the particular diagnostic task and, indeed, the anatomical region investigated/position of the pathology (LOFTHAG-HANSEN ET AL. 2011; NEVES ET AL. 2012). Image quality is described in terms of spatial resolution, contrast, noise and presence of artefacts (Tab. II) but on a simple level can be assessed relative to achieving the diagnostic task e.g. visualization of a periapical radiolucency, identification of the second mesiobuccal canal (MB2). A number of parameters impact on image quality: tube current, tube voltage, FOV, voxel size, number of projections and type of detector (MARET ET AL. 2012; SPIN-NETO ET AL. 2013; PAUWELS ET AL. 2015A). As previously established, there is a great array of CBCT devices available commercially, exhibiting a range of technical specifications, doses and image quality capabilities (HATCHER 2010; NEMTOI 2013). In order to achieve optimization of these devices, it is essential to use a standardized approach to assessing image quality (PAUWELS ET AL. 2011). Image quality can be assessed using subjective and objective methods.

Subjective Evaluation

This is considered as the benchmark when assessing image quality in relation to achieving a specific diagnostic task. It involves the standardized presentation of images (anthropomorphic phantoms, human skulls or jaws) to a specified number of observers who are provided with a scale to grade their ability to identify the presence of anatomical structures and/or grade the sufficiency of the image quality for a particular task e.g. root resorption, implant planning and periapical diagnosis (ALQERBAN ET AL. 2011; DURACK ET AL. 2011; ESPOSITO ET AL. 2011; LOFTHAG-HANSEN ET AL. 2011; SHELLEY ET AL. 2011). This technique is limited by its inherent subjectivity (inter-observer, intra-observer, case-sample variability, and the use of non-standardised skull and jaw models, which limits comparison) (TAPIOVAARA 2006; LOFTHAG-HANSEN ET AL. 2011). Furthermore, findings are often limited to the CBCT device investigated due to the large diversity in image quality between scanners (PAUWELS ET AL. 2012D).

Objective Evaluation

This involves quantitative measurement (on physical test objects) of physical factors such as: spatial resolution, contrast resolution, image density/pixel intensity, image noise, artefacts, on the basis that they equate to clinical image quality, using test phantoms (WATANABE ET AL. 2011). Identifying the need for a standardized phantom appropriate for dental CBCT, the SEDENTEXCT project developed a quality control phantom (SEDENTEXCT IQ phantom) which enables reproducible measurement of these technical image quality parameters on any CBCT device and thus is utilized for assessing device performance and quality control (PAUWELS ET AL. 2011; BAMBA ET AL. 2013; LUDLOW & WALKER 2013). While objective evaluation is essential for quality assurance (QA) of CBCT devices and these physical indices are germane, there is no direct means by which to relate them to clinical diagnostic accuracy (MARTIN ET AL. 1999; MÅNSSON 2000; WATANABE ET AL. 2011). Studies have shown a significant association of physical factors (modulation transfer function [MTF] and/or contrast-to-noise ratio [CNR]) with subjective image quality and related this to the ability to achieve a specific diagnostic task (CHOI ET AL. 2015; HIDALGO RIVAS ET AL. 2015; AL-OKSHI ET AL. 2017). Choi and co-workers (2015) demonstrated that a better physical image quality (higher MTF and CNR value) was required to achieve the clinical task of periapical diagnosis compared with implant planning in the mandible, the findings corresponding in part to a study on subjective image quality in relation to diagnostic task (LOFTHAG-HANSEN ET AL. 2011). However, both of these studies' findings were not related to dose measurements.

Is There Evidence That ALADA Is Practicable in a Range of Dental Diagnostic Tasks?

Reduced exposure protocols can be achieved while maintaining adequate image quality and thus diagnostic accuracy for a range of clinical tasks (EUROPEAN COMMISSION 2012; GOULSTON ET AL. 2015). These results relate to the diagnostic task investigated using specified CBCT scanner(s) and that technical specifications limit translation to all CBCT scanners. As previously discussed it has been established that size and position of FOV relative to the radiosensitive organs and the scanned individual have a substantial impact on dose optimization (DAVIES ET AL. 2012; PAUWELS ET AL. 2012A; THEODORAKOU ET AL. 2012; PAUWELS ET AL. 2013). Nonetheless, several *in vitro* studies specifically demonstrate that a reduction in exposure factors (kV, mA, exposure time – also altered through rotation time or voxel size/resolution) can be consistent with sufficient image quality to enable diagnosis in a range of clinical applications (Tab. III). Furthermore, two of these studies included dose measurements, recommending low-dose protocols for their respective diagnostic tasks (HIDALGO RIVAS ET AL. 2015; AL-OKSHI ET AL. 2017). One low dose protocol established a 50% dose reduction from the manufacturer's recommended protocol (HIDALGO RIVAS ET AL. 2015), which highlights the difficulty for practitioners in optimizing exposures. Other studies demonstrated the limitations of lower exposures relating to specific sites or pathology location (LOFTHAG-HANSEN ET AL. 2011; NEVES ET AL. 2012), reporting that although 180° rotations produced diagnostic images for maxillary implant planning, this was not the case for mandibular implant planning or periapical diagnosis (LOFTHAG-HANSEN ET AL. 2011). In the same way, Neves et al. (2012) suggested a reduced-dose scanning protocol pro-

duced images of diagnostic quality for detection of external root resorption (ERR) with the caveat that the position of root resorption may affect the ability to diagnose at lower exposures.

Generally, studies have reported that image quality is consistently degraded with reduced exposure factors (SUOMALAINEN ET AL. 2009; LUCKOW ET AL. 2011; PARSAR ET AL. 2013). The most commonly investigated diagnostic task with regard to optimization of exposure factors was that of implant planning, perhaps reflecting the almost ubiquitous use of CBCT in this dental application. Oddly, considering that children have a significantly increased radiation risk, there is a limited literature regarding optimization of exposure factors in orthodontic diagnostic tasks, while in the available studies it has been highlighted that orthodontic scanning in a child phantom resulted in on average an effective dose 36% greater than in the adult phantom (LUDLOW & WALKER. 2013). One orthodontic study found that reduced exposure time was consistent with maintenance of diagnostic accuracy (BROWN ET AL. 2009).

In conclusion, it is evident that radiation doses, significantly reduced from the manufacturer's recommendations can be achieved (via reduced kV, mA or time), while maintaining acceptable image quality and applied for certain diagnostic tasks and particular devices (Tab. III). Nonetheless, it has been emphasized that radical reductions in dose are futile if image quality degrades to the point of being non-diagnostic, thereby necessitating a repeat scan (LUDLOW & WALKER. 2013). Evidentially more research is needed, perhaps in collaboration with industry, to further assist practitioners in this important area.

How Valid Is the Research on Dose Optimization and Image Quality?

The majority of studies relating optimization to image quality are *in vitro* and thus of low hierarchical evidence-based standing (MARSHALL & SYKES 2011). Variations in CBCT device setting and properties make it impossible to reliably compare dose estimations from different studies. A systematic review of the literature on CBCT imaging in the oral and maxillofacial region highlighted inconsistent reporting on device settings and properties concluding, that a specific list of CBCT device parameters (e.g. exposure time, FOV, detector type, rotation arc etc.) should be documented to enable comparison (DE VOS ET AL. 2009). Unfortunately, this policy has not been universally adopted, but is reiterated in a more recent literature on optimization (EUROPEAN COMMISSION 2012; GOULSTON ET AL. 2016). These reviews highlight among other issues, the need for international compliance on a standardized method of accurately measuring patient dose using a standard commercially available phantom and the use of consistent reference standards were diagnostic accuracy is measured.

Diagnostic Efficacy of CBCT

Does CBCT Have a Greater Diagnostic Efficacy than Conventional Techniques?

The final section of this review analyses the evidence comparing the diagnostic efficacy of CBCT and conventional techniques for specific clinical tasks. If it is accepted that the diagnostic accuracy of CBCT is superior to conventional techniques, albeit at a higher dose to the patient, can this enhanced accuracy deliver a net benefit to the patient as evidenced by an impact on diagnosis, clinical decision-making and treatment outcome?

Tab. IV Hierarchal model of classification of diagnostic accuracy (FRYBACK & THORNBURY 1991)

Level of diagnostic efficacy	Definition and parameters measured
1. Technical Efficacy	Evaluates technical quality of imaging modality: i.e. noise, contrast, resolution, presence of artefacts and includes dose and dimensional accuracy.
2. Diagnostic Accuracy (DA) Efficacy	Evaluates accuracy of imaging modality in establishing a correct diagnosis when compared with the reference or "gold standard" technique: sensitivity, specificity, predictive values, ROC curves.
3. Diagnostic Thinking Efficacy	Evaluates the ability of the imaging modality to improve diagnostic decisions. Evidenced in before-and-after studies where an alternative diagnostic conclusion is made with new imaging modality when compared with diagnosis made using the existing conventional imaging modality.
4. Therapeutic Efficacy	Evaluates the impact that the imaging modality has on the choice of treatment. Evidenced in clinical studies (before-and-after) by observing the changes in treatment strategies where the new imaging modality scan is or is not supplied.
5. Patient Outcome Efficacy	Evaluates the impact of the imaging modality on patient outcome. Has this new diagnostic technique lead to an improved treatment strategy with a concomitant improved outcome for the patient, e.g. reduction in postoperative complications? This is assessed via randomized controlled trials (RCT) comparing patient outcome using new technique compared with existing "gold standard".
6. Societal Efficacy	Assesses the cost-benefit ratio of the imaging modality to society as a whole.

Critical appraisal of the literature on CBCT imaging efficacy is best facilitated by a hierarchal classification model, which categorizes six ascending levels of diagnostic efficacy (FRYBACK & THORNBURY 1991). The levels start with the simple goal of procuring the most accurate image and ascends to the complex target of improving patient outcome and societal impact with the aim of effecting evidence-based changes in patient care and health policy (Tab. IV). The lower tiers (levels 1 and 2) focus on image quality (NATIONAL COUNCIL ON RADIATION PROTECTION AND MEASUREMENTS 2005; KRUPINSKI ET AL. 2007) and diagnostic accuracy of CBCT (GHAEMINIA ET AL. 2009; MATZEN ET AL. 2013; PATEL ET AL. 2016). Such technical and diagnostic efficacy studies constitute the bulk of evidence in the literature and are less time consuming and expensive than study designs required at higher levels of efficacy, however, even these research domains are considered incomplete (EUROPEAN COMMISSION 2012; KIM ET AL. 2011; ROSEN ET AL. 2015; PETERSSON ET AL. 2012). While these principally lab-based studies are essential in establishing accuracy and report that CBCT exhibits higher sensitivity and specificity than intra-oral radiography for several diagnostic tasks (PETERSSON ET AL. 2012), albeit often in the absence of a relevant reference method, they do not provide any evidence of impact on patient care. Critically, accuracy studies should use a non-radiographic reference standard, which is an exact reflection of the true situation (MILEMAN & VAN DEN HOUT 2009) and could include histology (DE PAULA-SILVA ET AL. 2009) or intrasurgical visualization (QIAO ET AL. 2014; GHAEMINIA ET AL. 2009). *Ex vivo* simulation studies on dry skulls (DURACK ET AL. 2009; BRAUN ET AL. 2014) utilize direct visualization/measurement as a reference, however, it is questionable whether artificially created lesions represent either the true topography or borders of resorption or periodontal lesions (PETERSSON ET AL. 2012). Furthermore, considering the effect of patient movement on image quality, these studies are even further removed from the *in vivo* reality (NIKOLIC-JAKOBA ET AL. 2016).

Levels 3 and 4 evaluate whether an imaging modality can give rise to a change in diagnostic thinking or patient management

and therefore begin to consider impact on patient's health. Before-and-after studies are frequently used to investigate the impact of diagnostic and therapeutic choices at levels 3 and 4 (GUYATT ET AL. 1986; FRYBACK & THORNBURY 1991; MEADS & DAVENPORT 2009). The number of studies published at this level are much reduced compared to technical and diagnostic efficacy studies and the need for more research in these higher levels has been repeatedly highlighted (EUROPEAN COMMISSION 2012; BORNSTEIN ET AL. 2014; ROSEN ET AL. 2015; NIKOLIC-JAKOBA ET AL. 2016). Level 3 evidence suggests that CBCT does have an impact on diagnostic thinking efficacy in more complex and challenging cases with regards to implant placement and endodontics but cannot be justified for routine use (SHELLEY ET AL. 2015; EE J ET AL. 2014; MOTA DE ALMEIDA ET AL. 2015; AL-SALEHI & HORNER 2016). Additionally, in an orthodontic study on impacted canines, CBCT did increase confidence in diagnosis, especially for more critical information such as the labiopalatal position of the canine cusp tip (HANEY ET AL. 2010). Albeit, it was accepted that most impacted teeth can be accurately diagnosed/localized with conventional radiographs, nonetheless, there are undoubtedly cases which benefit from CBCT imaging (BJERKLIN & ERICSON 2006).

Therapeutic efficacy studies (level 4) revealed a range of CBCT impact on therapeutic decisions, perhaps influenced by study design (e.g. case selection method, teeth numbers, observer numbers/experience) and/or diagnostic task investigated. An endodontic study (24 teeth) revealed there was no significant difference in lesion size recorded or treatment strategy for periapical lesions in non-complex cases between periapical radiography (PR) and CBCT imaging (BALASUNDARUM ET AL. 2012). Although the numbers of subjects enrolled in the study are small, it does highlight that if CBCT does not actually alter the treatment plan, then the increased diagnostic accuracy of CBCT in recognizing apical periodontitis is of no real benefit (DE PAULA-SILVA ET AL. 2009; PATEL ET AL. 2009; VENSKUTONIS ET AL. 2014). It could be argued that the increased sensitivity of CBCT does diagnose AP lesions of smaller dimensions that would otherwise go undiagnosed and untreated by PR, this constituting an

increased therapeutic efficacy; however, this is not clear as the possibility of reduced specificity of CBCT in diagnosing AP has been reported *in vivo* (POPE ET AL. 2014). Pope's (2014) study reports on error in interpretation of the healthy periapex on CBCT scans and the inherent flaw of applying PR interpretation of health and disease to CBCT, thereby risking overdiagnosis (MOYNIHAN ET AL. 2012).

Other endodontic studies have demonstrated a significant impact of CBCT imaging on treatment planning choices in complex cases (EE ET AL. 2014; MOTA DE ALMEIDA ET AL. 2014; PATEL ET AL. 2016; RODRÍGUEZ ET AL. 2017; VENSUKUTONIS ET AL. 2014) with the general consensus being that the increased diagnostic information from a CBCT scan compared with conventional radiography had a substantial impact on treatment planning of high-difficulty cases (e.g. resorption, surgical cases). An orthodontic study showed that CBCT imaging evoked a change in treatment plan from conventional imaging but only in a minority of cases (27%), concluding that the additional diagnostic information did not translate to a significant change in treatment plan (HANEY ET AL. 2010). Implant studies reported a significant change in treatment plan with CBCT imaging for more challenging cases (narrower implants selected in the anterior mandible with CBCT) and high-risk anatomical regions (posterior jaw-longer implants selected using panoramic images) (SHELLEY ET AL. 2015; GUERRERO ET AL. 2014B); however, when all cases were considered a significant change in treatment plan between the two imaging modalities was not demonstrated. In general, these studies reflect the majority of current guidelines/position statements across the dental disciplines, which highlight that use of CBCT is not recommended routinely, but is only advisable in more complex cases where conventional radiography does not elucidate the diagnostic information required (AAE AND AAOMR 2011; EAO 2012 [HARRIS ET AL. 2012]; EUROPEAN COMMISSION 2012; FGDP [UK] 2013; ESE 2014). Notable exceptions to this conservative approach to CBCT prescription do exist (DRAGO & CARPENTIERI 2011; NOFFKE ET AL. 2011; AAOMR 2012 [TYNDALL ET AL. 2012]), with routine use of cross-sectional imaging in dental implant planning and treatment advocated, based on a reduced risk of neurosensory and neurovascular injury (ZIJDERVELD ET AL. 2008; RENTON ET AL. 2012; ROEDER ET AL. 2102; JACOBS ET AL. 2013). This routine CBCT use has been questioned by other groups who elicited opposing conclusions from the literature, highlighting the lack of evidence-based guidance in most national and international guidelines on implant dentistry and described their recommendations as largely expert opinion and consensus driven (BORNSTEIN ET AL. 2014; HORNER ET AL. 2015).

Ultimately, if clinicians are exposing patients to diagnostic ionizing radiation which is of significantly higher dose than that of the existing diagnostic imaging modality of choice, the new imaging modality should demonstrate a positive impact on patient outcome (level 5 – Patient outcome efficacy), preferably in a cost-effective manner (level 6 – Societal efficacy). Randomized controlled trials (RCTs) are the optimal study design to assess these levels of accuracy (FRYBACK & THORNBURY 1991). Generally, RCTs are expensive and time consuming, often resulting in low subject numbers and underpowered studies (ROEDER ET AL. 2012). Furthermore, they can be ethically difficult or impossible to perform with regards to diagnostic imaging modalities (MILEMAN & VAN DEN HOUT 2009) and it has been argued that due to their longitudinal nature and the fast pace of CBCT technology development, their results can be redundant

even before publication (KIM ET AL. 2011). Perhaps not surprisingly there are very few studies published which assess patient outcome efficacy (Level 5). Three studies investigating surgical extraction of impacted mandibular third molars (GUERRERO ET AL. 2014A; GHAEMINIA ET AL. 2015; PETERSEN ET AL. 2016) failed to demonstrate any beneficial impact of CBCT over panoramic imaging on patient related outcomes (i.e. neurosensory disturbances and other postoperative complications). Although, it should be recognized that the studies were small, with an inadequate sample size for a comparative prospective study (ROEDER ET AL. 2012). A recent systematic review (MATZEN & WENZEL 2015) concluded that for most cases, periapical or panoramic imaging may be sufficient for removal of mandibular third molars; however, CBCT may be indicated where conventional imaging reveals one or more signs of close contact between the tooth and the mandibular canal (ROOD & SHEBAB 1990), but only if it is believed that CBCT imaging will subsequently elicit a change in treatment plan or patient outcome. This conclusion is open to subjective interpretation and probably encourages a pattern of CBCT prescription for impacted mandibular third molars that correlates with the clinician's experience. A further RCT, comparing the impact of panoramic and CBCT imaging on periradicular surgery, elicited a significant difference in operator-related outcome (operating time), but this did not appear to have any positive ramifications on patient outcome (KURT ET AL. 2014).

Societal efficacy studies (level 6) aim to prove that implementation of this diagnostic imaging modality is an efficient use of societal resources and can provide medical benefits to society. There is a paucity of RCTs investigating societal efficacy. One prospective RCT reported on the absolute and relative costs of a CBCT scan compared with that of a panoramic examination undertaken for third molar surgery, identifying a 3–4 times greater cost associated with CBCT than panoramic imaging but there was no significant difference in resources consumed between the imaging groups, either surgically or postsurgery (PETERSEN ET AL. 2014). The same group also published an epidemiological study in Denmark (PETERSEN ET AL. 2015), which highlighted the higher economic implications of potential routine use of CBCT in extraction of mandibular third molar teeth. Importantly, this study actually considers the radiation risk implications associated with this potential policy change (calculation of cancer incidence – 0.46 per year) which is necessary when contemplating societal efficacy. Other level 6 studies are descriptive; a cost analysis study noted that a demonstrated cost-effectiveness of CBCT imaging in one healthcare system cannot necessarily be translated to another (CHRISTELL ET AL. 2012). A periodontal case series reported that CBCT-based treatment decisions for maxillary molars with furcation defects can lead to time and cost benefits when compared with conventional radiography in a Swiss dental health setting (WALTER ET AL. 2012). Based on the cost analyses performed, it was concluded that CBCT as an additional diagnostic measure is only justified when more invasive therapies are planned and, considering the potential increased radiation risk associated with additional imaging, cases should be judged on an individual basis. Again, this conclusion is open to subjective interpretation.

In conclusion there is a lack of studies exhibiting the impact of CBCT at higher levels of efficacy (EUROPEAN COMMISSION 2012; MATZEN & WENZEL 2015; ROSEN 2015; NIKOLIC-JAKOBA ET AL. 2016), with one recent review concluding that the effectiveness of

CBCT in a range of dental disciplines has barely been evaluated (MATZEN & WENZEL 2015). Unfortunately, regardless how compelling the results of the technical and diagnostic accuracy efficacy studies, this literature is not indicative of any translational benefit of CBCT to patient's treatment and outcome or indeed to society.

Conclusions

- Conventional radiography is limited by the inability to describe the 3D anatomy of teeth and their related structure. It has therefore been recommended that CBCT be used in select cases in which conventional radiography cannot supply satisfactory diagnostic information.
- CBCT is a more sensitive diagnostic tool than conventional radiography but delivers a significantly greater patient dose. Therefore, unless the benefit to the patient can be justified there is a risk of overexposure. Furthermore, there is concern that with increased diagnostic sensitivity there is a loss of specificity which may result in over-representation of disease, which highlights a need for establishing an "atlas of normal" particular to CBCT, in order to correctly diagnose pathology.
- The clinician in practice prescribes, exposes, analyses and reports on the CBCT image. Therefore, appropriate training in justification, acquisition and interpretation is paramount.
- There is a lack of evidence that CBCT imaging has a significant impact on decision-making and treatment outcome. Therefore, at present, the clinician remains unsupported in their justification of CBCT imaging.
- With an awareness of the potential stochastic radiation risks of CBCT, being particularly pertinent to the young, judicious case selection is essential to ensure that the benefits-risk ratio remains in favour of the individual patient. Guidelines constructed from the best available evidence serve to aid the clinician's justification. Unfortunately, these available guidelines are of varying quality with the majority being based on expert opinion. It is important that a more critical systematic approach is adopted in the formulation of new guidelines.
- It is accepted in CBCT that FOV height and relation of the FOV to the radiosensitive organs are the main determinants of effective dose. Additionally, optimization of exposure and imaging parameter factors, can achieve significant dose reductions, while maintaining image quality for a range of diagnostic tasks, but this is not necessarily translatable to all devices. Further development of low dose protocols in key diagnostic areas would greatly aid the clinician.
- Despite the lack of evidence on the efficacy of CBCT, its use is expanding rapidly in dental practice. It is a lucrative, industry-driven business, sold on the basis of improved, attractive and high-quality imaging. Critical evaluation of manufacturer's advice and default protocols necessitates appropriate undergraduate and postgraduate training and knowledge of the evidence base regarding CBCT imaging.
- The current literature on CBCT imaging reveals the need for consistent and standardized testing and reporting to allow effective comparisons of dose calculations and optimization techniques on image quality. Diagnostic accuracy studies do not always reflect the clinical situation and inconsistent reference standards make ready comparison between results impossible. Notably, higher hierarchical level studies are rare, with only four RCTs assessing clinical outcome efficacy. Nevertheless, for the purpose of establishing robust guidelines for

appropriate use of CBCT, research in the future should be directed at higher level clinical studies.

Zusammenfassung

Einleitung

Die Möglichkeit, hochauflösende dreidimensionale (3D) Röntgenbilder zu erstellen, hat die digitale Volumentomografie (DVT) in der zahnärztlichen Praxis immer populärer gemacht. Einige inhärente Probleme der konventionellen zweidimensionalen (2D) Radiografie wie beispielsweise Überlagerungen oder andere anatomisch bedingte Einschränkungen in der Interpretierbarkeit («anatomical noise») können dabei überwunden werden. In Anbetracht der stetig steigenden Nutzung der DVT, gerade auch bei zahnärztlichen Erstbehandlungen, haben es sich die Autoren dieser Übersichtsarbeit zum Ziel gemacht, herauszufinden, welche evidenzbasierte Information dem Kliniker zur Verfügung steht, um das mit der DVT einhergehende erhöhte Bestrahlungsrisiko zu rechtfertigen, und dieses allenfalls zu reduzieren, um noch immer eine diagnostisch akzeptable Bildqualität zu erhalten.

Material und Methoden

Die Literatur über Strahlendosis und das damit einhergehende Patientenrisiko wurde eingehend untersucht. Anschliessend wurde geschaut, wie sich die Strahlendosis optimieren lässt und wie sich eine solche Optimierung auf die Bildqualität auswirkt. Obwohl es als anerkannt gilt, dass DVT die Diagnostik in vielen Gebieten der Zahnmedizin verbessern kann, ist nicht unbedingt klar, inwieweit dadurch Behandlungsentscheide und Behandlungserfolge tatsächlich verbessert werden können. Um diese Punkte genauer anzuschauen, wurden die Evidenz und die Validität der zum Thema vorhandenen Studien geprüft.

Resultate

Die DVT-basierte 3D-Visualisierung des maxillofazialen Skeletts kann im Vergleich zur konventionellen (2D) Radiografie mehr diagnostische Informationen liefern. Die DVT ist dabei allerdings mit einer erhöhten Strahlenbelastung verbunden, was die Wichtigkeit einer strikten Befolgung von Indikationsstellung, Rechtfertigung und Bildoptimierung unterstreicht. Bei der Durchsicht der zum Thema vorhandenen Literatur wurde klar, dass die Optimierung bzw. Reduktion der Strahlendosis für eine gegebene diagnostische Fragestellung eine genügende Bildqualität liefern kann. Es ist allerdings so, dass die meisten dieser Studien ein niedriges Evidenzniveau aufweisen und dass ein standardisiertes Vorgehen weitestgehend fehlt. Zur Optimierung der Strahlendosis gibt es wenig praktische Hilfe für Zahnärzte, und existierende Protokolle lassen sich nicht auf jedes Gerät übertragen. Hinzu kommt, dass die Bedienungsanleitungen der Geräte normalerweise keine Aussagen zur Dosisreduktion machen. Es gibt wenig Daten, die eine Verbesserung der Diagnostik und des entsprechenden Behandlungsentscheids dank DVT aufgezeigt haben. Weiterhin gibt keine Evidenz für einen Effekt der DVT auf den Behandlungserfolg.

Diskussion

Die bestehende Literatur unterstreicht die Notwendigkeit, spezifische Richtlinien zur Dosisoptimierung bei gegebenen diagnostischen Fragestellungen zu erarbeiten. Zudem müssen klinische Studien durchgeführt werden, um den Einfluss der DVT auf höhere Ebenen der diagnostischen Wirksamkeit zu untersuchen.

Résumé

Introduction

La tomographie volumique numérique (TVN) (ou Cone Beam CT, CBCT) est de plus en plus populaire en pratique médico-dentaire, car elle permet d'obtenir des images radiographiques tridimensionnelles (3D) en haute résolution. Certaines difficultés inhérentes à la radiographie conventionnelle bidimensionnelle (2D), telles que les superpositions ou autres limitations d'interprétation liées au «bruit anatomiques», peuvent être surmontées de cette manière. En raison de l'utilisation croissante de la TVN, notamment lors du traitement médico-dentaire initial, les auteurs de ce travail de revue ont cherché à identifier les informations factuelles obtenues ainsi par le clinicien et justifiant le risque inhérent à l'augmentation de l'exposition aux rayons X associée à cette méthode; en outre, les auteurs se sont demandés comment réduire au mieux ce risque tout en préservant une qualité d'image acceptable du point de vue du diagnostic.

Matériel et méthodes

La littérature sur la dose de rayonnement et le risque associé pour la santé du patient a été étudiée de façon approfondie. Puis les auteurs ont cherché à savoir comment optimiser la dose de rayonnement, et dans quelle mesure une telle optimisation affecte la qualité d'image. Même s'il est généralement admis que la TVN permet d'améliorer le diagnostic dans de nombreux domaines de la médecine dentaire, on ne sait pas très clairement dans quelle mesure cette technique d'imagerie permet réellement d'améliorer les décisions thérapeutiques, et donc les résultats des traitements. Afin d'examiner de plus près ces différents aspects, le degré d'évidence et la validité des études existantes sur ce sujet ont été évalués.

Résultats

Par rapport à la radiographie conventionnelle (2D), la visualisation 3D du squelette maxillo-facial par TVN peut fournir davantage d'informations diagnostiques. Cependant, la TVN est associée à une exposition accrue aux radiations, d'où l'importance du respect strict des indications de cet examen, de ses justifications et de l'optimisation de l'image. L'étude de la littérature existante sur ce sujet a montré clairement que l'optimisation, respectivement la réduction de la dose de rayonnement en fonction d'une question diagnostique donnée peut être compatible avec une qualité d'image suffisante. Cependant, la plupart de ces études ont un faible niveau de preuve et les procédures suivies ne sont généralement pas standardisées. Dans ces études, les médecins-dentistes trouvent peu d'indications pratiques pour optimiser la dose de rayonnement, et les protocoles existants ne peuvent pas être transposés à tous les appareils. En outre, les guides d'utilisation des appareils ne donnent généralement pas d'indications sur la réduction de la dose. Les données qui ont montré une amélioration du diagnostic et de la décision thérapeutique correspondante grâce à la TVN sont peu nombreuses. De plus, il n'existe à ce jour aucune évidence d'un effet positif de la TVN sur les résultats thérapeutiques.

Discussion

La littérature existante souligne la nécessité de développer des directives spécifiques pour l'optimisation de la dose en fonction des différentes questions diagnostiques qui peuvent se poser. En outre, des études cliniques doivent être réalisées pour évaluer l'influence de la TVN quant à la possibilité d'obtenir des niveaux plus élevés d'efficacité diagnostique.

References

- ALAMRI H M, SADRAMELI M, ALSHALHOOB M A, SADRAMELI M, ALSHEHRI M A: Applications of CBCT in dental practice: a review of the literature. *Gen Dent* 60: 390–400 (2012)
- AL-EKRISH A A: Effect of exposure time on the accuracy and reliability of cone beam computed tomography in the assessment of dental implant site dimensions in dry skulls. *Saudi Dent J* 24: 127–134 (2012)
- AL NAJJARA, COLOSSI D, DAUER L T, PRINS R, PATCHELL G, BARNETS I, GOREN A D, FABER R D: Comparison of adult and child radiation equivalent doses from 2 dental cone-beam computed tomography units. *Am J Orthod Dentofacial Orthop* 143: 784–792 (2013)
- AL-OKSHI A, THEODORAKOU C, LINDH C: Dose optimization for assessment of periodontal structures in cone beam CT examinations. *Dentomaxillofac Radiol* 46: 20160311 (2017)
- ALQERBAN A, JACOBS R, FIEUWS S, NACKAERTS O, WILLEMS G, SEDENTEXCT PROJECT CONSORTIUM: A comparison of six cone beam computed tomography systems for image quality and detection of simulated canine impaction-induced external root resorption in maxillary lateral incisors. *Am J Orthod Dentofacial Orthop* 140: 129–139 (2011)
- AL-SALEHI S K, HORNER K: Impact of cone beam computed tomography (CBCT) on diagnostic thinking in endodontics of posterior teeth: A before-after study. *J Dent* 53: 57–63 (2016)
- AMERICAN ASSOCIATION OF ENDODONTISTS, AMERICAN ACADEMY OF ORAL AND MAXILLOFACIAL RADIOLOGY: Use of cone-beam computed tomography in endodontics Joint Position Statement of the American Association of Endodontists and the American Academy of Oral and Maxillofacial Radiology. *Oral Surg Oral Med Oral Pathol Oral Radiol Endod* 111: 234–237 (2011)
- AMERICAN THYROID ASSOCIATION (ATA): Issues policy statement on minimizing radiation exposure from medical, dental diagnostics The use of cone-beam computed tomography in dentistry: an advisory statement from the American Dental Association Council on Scientific Affairs. *J Am Dent Assoc* 143: 899–902 (2012)
- ARAI Y, TAMMISALO E, IWAI K, H ASHIMOTO K, SHINODA K: Development of a compact computed tomographic apparatus for dental use. *Dentomaxillofac Radiol* 28: 245–248 (1999)
- ARBEITSGEMEINSCHAFT DER WISSENSCHAFTLICHEN MEDIZINISCHEN FACHGESELLSCHAFTEN (AWMF): s2k-Leitlinie Dentale digitale Volumentomographie Version Nr. 9 (2013)
- BABA R, UEDA K, OKABE M: Using a flat-panel detector in high resolution cone beam CT for dental imaging. *Dentomaxillofac Radiol* 33: 285–290 (2004)
- BALASUNDARAM A, SHAH P, HOEN M M, WHEATER M A, BRINGAS J S, GARTNER A, GEIST J R: Comparison of cone-beam computed tomography and periapical radiography in predicting treatment decision for periapical lesions: a clinical study. *Int J Dent Article ID* 920815 (2012)
- BAMBA J, ARAKI K, ENDO A, OKANO T: Image quality assessment of three cone beam CT machines using the SEDENTEXCT CT phantom. *Dentomaxillofac Radiol* 42: 20120445 (2013)
- BARRET H H, MYERS K J, HOESCHEN C, KUPINSKI M A, LITTLE M P: Task-based measures of image quality and their relation to radiation dose and patient risk. *Phys Med Biol* 60: R1–R75 (2015)
- BECHARA G, MCMAHN A, NASSEH I, GEHA H, HAYEK E, KHAWAM G, M, NOUJEIM M: Number of basis images effect on detection of root fractures in endodontically treated teeth using a cone beam computed tomography machine: an in vitro study. *Oral Surg Oral Med Oral Pathol Oral Radiol* 115: 676–681 (2013)
- BERG B I, GERTSCH A, ZEILHOFER H F, SCHWENZER-ZIMMERER K, BERG S, HASSFELD S, JURGENS P: Cone beam computed tomography and radiation dosage: application frequency and knowledge of dentists in Switzerland. *Swiss Dent J* 124: 419–433 (2014)
- BJERKLIN K, ERICSON S: How a computerized tomography examination changed the treatment plans of 80 children with retained and ectopically positioned maxillary canines. *Angle Orthod* 76: 43–51 (2006)
- BORISOVA R, INGILIZOVA C, VASSILEVA J: Patient dosimetry in pediatric diagnostic radiology. *Radiat Prot Dosim* 129: 155–159 (2008)

- BORNSTEIN M M, SCARFE W C, VAUGHN V M, JACOBS R:** Cone Beam Computed Tomography in Implant Dentistry: A Systematic Review Focusing on Guidelines, Indications, and Radiation Dose Risks. *Oral Maxillofac Implants* 29 (SUPPL): 55–77 (2014)
- BRAUN X, RITTER L, JERVØE-STORM P M, FRENTZEN M:** Diagnostic accuracy of CBCT for periodontal lesions. *Clin Oral Investig* 18: 1229–1236 (2014)
- BROWN A A, SCARFE W C, SCHEETZ J P, SILVEIRA A M, FARMAN A G:** Linear accuracy of cone beam CT derived 3D images. *Angle Orthod* 79: 150–157 (2009)
- BROWN J, JACOBS R, LEVREING JAGHAGEN E, LINDH C, BAKSI G, SCHULZE D, SCHULZE R:** Basic training requirements for the use of dental CBCT by dentists: a position paper prepared by the European Academy of Dentomaxillofacial Radiology. *Dentomaxillofac Radiol* 43: 20130291 (2014)
- CASSOLA V F, MILIAN F M, KRAMER R, DE OLIVEIRA LIRA C S A, KHOURY H J:** Standing adult human phantoms based on the 10th, 50th and 90th mass and height percentiles of male and female Caucasian populations. *Phys Med Biol* 56: 3749–3772 (2011)
- CHOI E, FORD N L:** Measuring absorbed dose for i-Cat CBCT examinations in child, adolescent and adult phantoms. *Dentomaxillofac Radiol* 44: 20150018 (2015)
- CHOI J W, LEE S S, CHOI S C, HEO M S, HUH K H, YI W J, KANG S R, HAN D H, KIM E K:** Relationship between physical factors and subjective image quality of cone-beam computed tomography images according to diagnostic task. *Oral Surg Oral Med Oral Pathol Oral Radiol* 119: 357–365 (2015)
- CHRISTELL H, BIRCH S, HEDESIU M, HORNER K, IVANAUŠ-KAITĖ D, NACKAERTS O, ROHLIN M, LINDH C, SEDENT-EXCT CONSORTIUM:** Variation in costs of cone beam CT examinations among healthcare systems. *Dentomaxillofac Radiol* 41: 571–577 (2012)
- DAVIES J, JOHNSON B, DRAGE N A:** Effective doses from cone beam CT investigation of the jaws. *Dentomaxillofac Radiol* 41: 30–36 (2012)
- DE MAN B, BASU S:** Distance-driven projection and backprojection in three dimensions. *Phys Med Biol* 49: 2463–2475 (2004)
- DE PAULA-SILVA F W, WU M K, LEONARDO M R, BEZERRA L A, WESSELINK P R:** Accuracy of Periapical Radiography and Cone-Beam Computed Tomography Scans in Diagnosing Apical Periodontitis Using Histopathological Findings as a Gold Standard. *J Endod* 35: 1009–1012 (2009)
- DE VOS W, CASSELMAN J, SWEENEY G R:** Cone beam computerized tomography (CBCT) imaging of the oral and maxillofacial region: a systematic review of the literature. *Dentomaxillofac Radiol* 38: 609–625 (2009)
- DÖLEKOĞLU S, FIŞEKÇIOĞLU E, İGÜY M İ, İGÜY Y:** The usage of digital radiography and cone beam computed tomography among Turkish dentists. *Dentomaxillofac Radiol* 40: 379–384 (2011)
- DONALDSON K, O'CONNOR S, HEATH N:** Dental cone beam CT image quality possibly reduced by patient movement. *Dentomaxillofac Radiol* 42: 91866873 (2013)
- DRAGE N, CARMICHAEL F, BROWN J:** Radiation protection: protection of patients undergoing cone beam computed tomography examinations. *Dent Update* 37: 542–544, 547–548 (2010)
- DRAGO C, CARPENTIERI J:** Treatment of maxillary jaws with dental implants: guidelines for treatment. *J Prosthodont* 20: 336–347 (2011)
- DULA K, BENIC G I, BORNSTEIN M, DAGASSAN-BERNDT D, FILIPPI A, HICKLIN S, KISSLINGJEGGER F, LUEBBERS H-T, SCULEAN A, SEQUEIRA-BYRON P, WALTER C, ZEHNDER M:** SADMFR Guidelines for the use of cone-beam computed tomography/digital volume tomography endodontics, periodontology, reconstructive dentistry, pediatric dentistry. A consensus workshop organized by the Swiss association of dentomaxillofacial radiology. *S Dent J* 125: 945–953 (2015)
- DURACK C, PATEL S, DAVIES J, WILSON R, MANNOCCI F:** Diagnostic accuracy of small volume cone beam computed tomography and intraoral periapical radiography for the detection of simulated external inflammatory root resorption. *Int Endod J* 44: 136–147 (2011)
- EE J, FAYD M I, JOHNSON B R:** Comparison of endodontic diagnosis and treatment planning decisions using cone-beam volumetric tomography versus periapical radiography. *J Endod* 40: 910–916 (2014)
- ESPOSITO S, CARDAROPOLI M, COTTI E:** A suggested technique for the application of the cone beam computed tomography periapical index. *Dentomaxillofac Radiol* 40: 506–512 (2011)
- EUROPEAN COMMISSION:** Radiation Protection 1136. European Guidelines on Radiation Protection in Dental Radiology. Luxembourg: Office for official Publications of the European Communities. (2004)
- EUROPEAN COMMISSION:** Radiation protection 172: Evidence based guidelines on cone beam CT for dental and maxillofacial radiology. Luxembourg: Office for Official publications of the European Communities. (2012)
- EUROPEAN SOCIETY OF ENDODONTOLOGY, PATEL S, DURACK C, ABELLA F, ROIG M, SHEMES H, LAMBRECHTS P, LEMBERG K:** European Society of Endodontology position statement: the use of CBCT in endodontics. *Int Endod J* 47: 502–504 (2014)
- EZELDEEN M, STRATIS A, COUCKE W, CODARI M, POLITIS, JACOBS R:** As Low Dose as Sufficient Quality: Optimization of Cone-beam Computed Tomographic Scanning Protocol for Tooth Autotransplantation Planning and Follow-up in Children. *J Endod* 43: 210–217 (2017)
- HORNER K, EATON K A:** Selection criteria for dental radiography. Faculty of General Dental Practice 3rd edn. London, UK (2013)
- FRYBACK D G, THORNBURY J R:** The efficacy of diagnostic imaging. *Med Decis Making* 11(2): 88–94 (1991)
- GHAEMINIA H, MEIJER G J, SOEHARDI A, BORSTLAP W A, MULDER J, BERGE S J:** Position of the impacted third molar in relation to the mandibular canal. Diagnostic accuracy of cone beam computed tomography compared with panoramic radiography. *Int J Oral Maxillofac Surg* 38: 964–971 (2009)
- GHAEMINIA H, GERLACH N L, HOPPENREIJS TH J M, KICKEN M, DINGS J P, BORSTLAP W A, DE HAAN T, BERGE S J, MEIJER G J, MAAL T J:** Clinical relevance of cone beam computed tomography in mandibular third molar removal: A multicentre, randomised, controlled trial. *J Craniomaxillofac Surg* 43: 2158–2167 (2015)
- GOULSTON R, DAVIES J, HORNER K, MURPHY F:** Dose optimization by altering the operating potential and tube current exposure time product in dental cone beam CT: a systematic review. *Dentomaxillofac Radiol* 45: 20150254 (2016)
- GUERRERO M E, BOTETANO R, BELTRAN J, HORNER K, JACOBS R:** Can preoperative imaging help to predict postoperative outcome after wisdom tooth removal? A randomized controlled trial using panoramic radiography versus cone beam CT. *Clin Oral Invest* 18: 335–342 (2014a)
- GUERRERO M E, NOIEGA J, CASTRO C, JACOBS R:** Does cone-beam CT alter treatment plans? Comparison of preoperative implant planning using panoramic versus cone-beam CT images. *Imaging Science in Dentistry* 44: 121–128 (2014b)
- GUYATT G H, TUGWELL P X, FEENY D H, DRUMMOND M F, HAYNES R B:** The role of before-after studies of therapeutic impact in the evaluation of diagnostic technologies. *Journal Chronic Dis* 39: 295–304 (1986)
- HALL E J, BRENNER D J:** Cancer risks from diagnostic radiology. *Br J Radiol* 81: 362–378 (2008)
- HANEY E, GANSKY S A, LEE J S, JOHNSON E, MAKI K, MILLER A J, HUANG J C:** Comparative analysis of traditional radiographs and cone-beam computed tomography volumetric images in the diagnosis and treatment planning of maxillary impacted canines. *Am J Orthod Dentofacial Orthop* 137: 590–597 (2010)
- HARRIS D, HORNER K, GRÖNDAHL K, JACOBS R, HELMROTT E, BENIC G I, BORNSTEIN M M, DAWOOD A, QUIRYNEN M:** E.A.O. guidelines for the use of diagnostic imaging in implant dentistry 2011. A consensus workshop organized by the European Association for Osseointegration at the Medical University of Warsaw. *Clin Oral Implants Res* 23: 1243–1253 (2011)
- HASHEM D, BROWN J E, PATEL S, MANNOCCI F, DONALDSON A N, WATSON T, BANERJEE A:** An In Vitro Comparison of the Accuracy of Measurements Obtained from High- and Low-resolution Cone-beam Computed Tomography Scans. *J Endod* 39: 394–397 (2013)
- HATCHER D C:** Operational principles for cone-beam computed tomography. *J Am Dent Assoc* 141 Suppl 3: 3S–6S (2010)
- HEALTH PROTECTION AGENCY:** Guidance on the safe use of dental cone beam CT (Computed Tomography) Equipment. HPA–CRCE–010. Chilton: Health Protection Agency (2010)
- HIDALGO RIVAS J A, DAVIES J, HORNER K, THEODORAKOU C:** Effectiveness of thyroid gland shielding in dental CBCT using a paediatric anthropomorphic phantom. *Dentomaxillofac Radiol* 44 (3): 20140285 (2015)
- HIDALGO RIVAS J A, HORNER K, THIRUVENKATACHARI B, DAVIES J, THEODORAKOU C:** Development of a low-dose protocol for cone beam CT examination of the anterior maxilla in children. *Br J Radiol* 88: 20150559 (2015)
- HIRSCH E, WOLF U, HEINICKE F, SILVA M A:** Dosimetry of the cone beam computed tomography Veraviewepocs 3D compared with the 3D Accuitomo in different fields of view. *Dentomaxillofac Radiol* 37: 268–273 (2008)
- HOL C, HELLÉN-HALME K, TORGENSEN G, NILSSON M, MØYSTAD A:** How do dentists use CBCT in dental clinics? A Norwegian nationwide survey. *Acta Odontologica Scandinavica* 73: 195–201 (2015)
- HOLROYD J R, WALKER A:** Recommendations for the design of X-ray facilities and quality assurance of dental cone beam CT (computed tomography) system: Health Protection Agency HPA–RPD–065 (2010)
- HORNER K, ISLAM M, FLYGARE L, TSIKLAKIS K, WHITES E:** Basic principles for use of dental cone beam CT: consensus guidelines of the European Academy of Dental and Maxillofacial Radiology. *Dentomaxillofac Radiol* 38: 187–195 (2009)
- HORNER K, JACOBS R, SCHULZE R:** Dental CBCT equipment and performance issues. *Radiat Prot Dosimetry* 153: 212–218 (2013)
- HORNER K, O'MALLEY L, TAYLOR K, GLENNY A M:** Guidelines for clinical use of CBCT: a review. *Dentomaxillofac Radiol* 44: 20140225 (2015)
- IRCP:** Publication 60. Recommendations of the International Commission on Radiological Protection. *Ann IRCP*: 21 (1990)
- IRCP:** Publication 103. The 2007 Recommendations of the International Commission on Radiological Protection. *Ann IRCP*: 37 (2007)
- JACOBS R, QUIRYNEN M, BORNSTEIN M M:** Neurovascular disturbances after implant surgery. *Periodontol* 2000 66: 188–202 (2013)
- KALENDER W A, BUCHENAU S, DEAK P, KELLERMEIER M, LANGNER O, VAN STRATEN M, VOLLMAR S, WILHARM S:** Technical approaches to the optimization of CT. *Phys Med* 24: 71–79 (2008)
- KAMBOROĞLU K, KURSUN S:** A comparison of the diagnostic accuracy of CBCT images of different voxel resolutions used to detect simulated small internal resorption cavities. *Int Endod J* 43: 798–807 (2010)

- KARMAZYN B, LIANG Y, KLAHR P, JENNINGS S G: Effect of Tube Voltage on CT Noise Levels in Different Phantom Sizes. *Am J Roentgenol* 200; 1001–1005 (2013)
- KILJUNEN T, KAASALAINEN T, SUOMALAINEN A, KORTESNIEMI M: Dental cone beam CT: A Review. *Phys Med* 31: 844–860 (2015)
- KIM I, PATEL M, HIRT S, KANTOR M: Clinical research and diagnostic efficacy studies in the oral and maxillofacial radiology literature: 1996–2005. *Dentomaxillofac Radiol* 40: 274–281 (2011)
- KIM D S, RASHSURENO, KIM E K: Conversion coefficients for the estimation of effective dose in cone-beam CT. *Imaging Sci Dent* 44: 21–29 (2014)
- KOIVISTOJ, KILJUNEN T, TAPIOVAARA M, WOLFF J, KORTESNIEMI M: Assessment of radiation exposure in dental cone-beam computerized tomography with the use of metal-oxide semiconductor field-effect transistor (MOSFET) dosimeters and Monte Carlo simulations. *Oral Surg Oral Med Oral Pathol Oral Radiol* 114: 393–400 (2012)
- KRUPINSKI E A, WILLIAMS M B, ANDRIOLE K, STRAUSS K J, APPLGATE K, WYATT M, BJORK S, SEIBERT J A: Digital radiography image quality: image processing and display. *J Am Coll Radiol* 4: 389–400 (2007)
- KURT S N, ÜSTÜN Y, ERDOGAN Ö, EVLICE B, YOLDAS O, ÖZTUNC H: Outcomes of periradicular surgery of maxillary first molars using a vestibular approach: A prospective, clinical study with one year follow up. *J Oral Maxillofac Surg* 72: 1049–1061 (2014)
- KWONG J C, PALOMO J M, LANDERS M A, FIGUEROA A, HANS M G: Image quality produced by different cone-beam computed tomography settings. *Am J Orthod Dentofacial Orthop* 133: 317–327 (2008)
- KYRIACOU Y, KOLDITZ D, LANGNER O, KRAUSE J, KALENDER W: Digital Volume Tomography (DVT) and Multislice Spiral CT (MSCT): An Objective Examination of Dose and Image Quality. *Fortschr Röntgenstr* 183: 144–153 (2011)
- LARSSON J P, PERSLIDEN J, SANDBORG M, CARLSSON G A: Transmission ionization chambers for measurements of air collision kerma integrated over beam area. Factors limiting the accuracy of calibration. *Phys Med Biol* 41: 2831–2398 (1996)
- LENNON S, PATEL S, FOSCHI F, WILSON R, DAVIES J, MANNOCCI F: Diagnostic Accuracy Of Limited-Volume cone-beam computed tomography in the detection of periapical bone loss: 360° scans versus 180° scans. *Int Endod J* 44: 11181127 (2011)
- LI X, SAMEI E, SEGARS W P, STURGEON G M, COLSHER J G, TONCHEYA G, YOSHIZUMI T T, FRUSH D P: Patient-specific radiation dose and cancer risk estimation in CT: part II. application to patients. *Med Phys* 38: 408–419 (2011)
- LIEDKE G S, DA SILVEIRA H E, DA SILVEIRA H L, DUTRA V, DE FIGUEIREDO J A: Influence of voxel size in the diagnostic ability of cone beam tomography to evaluate simulated external root resorption. *J Endod* 35: 233–235 (2009)
- LOFTHAG-HANSEN S, THILANDER-MANG A, EKESTUBBE A, HELMROT E, GRONDAHL K: Calculating effective dose on a cone beam computed tomography device: 3D Accutomo and 3D Accutomo FPD. *Dentomaxillofac Radiol* 37: (2008)
- LOFTHAG-HANSEN S: Cone beam computed tomography radiation dose and image quality assessments. *Swed Dent J Suppl* 209: 4–55 (2010)
- LOFTHAG-HANSEN S, THILANDER-KING A, GRONDAHL K: Evaluation of subjective image quality in relation to diagnostic task for cone beam computed tomography with different fields of view. *Eur J Radiol* 80: 483–488 (2011)
- LOUBELE M, BOGAERTS R, VAN DIJCK E, PAUWELS R, VANHEUSDEN S, SUETENS P, MARCHAL G, SANDERINK G, JACOBS R: Comparison between effective radiation dose of CBCT and MSCT scanners for dentomaxillofacial applications. *Eur J Radiol* 71: 461–468 (2009)
- LUCKOW M, MEYHLE H, BECKMANN F, DAGASSAN-BERNDT D, MÜLLER B: Tilting the jaw to improve the image quality or to reduce the dose in cone-beam computed tomography. *Eur J Radiol* 80: e389–e393 (2011)
- LUDLOW J B, DAVIES-LUDLOW L E, BROOKS S L, HOWER-TON W B: Dosimetry of 3 CBCT devices for oral and maxillofacial radiology: CB Mercury, NewTom 3 G and i-Cat. *Dentomaxillofac Radiol* 35: 219–226 (2006)
- LUDLOW J B, DAVIES-LUDLOW L E, WHITE S C: Patient risk related to common dental radiographic examinations: the impact of 2007 International Commission on Radiological Protection recommendations regarding dose calculation. *J Am Dent Assoc* 139: 1237–1243 (2008)
- LUDLOW J B, IVANOVIC M: Comparative dosimetry of dental CBCT devices and 64-slice CT for oral and maxillofacial radiology. *Oral Surg Oral Med Oral Pathol Oral Radiol Endod* 106: 106–114 (2008)
- LUDLOW J B: Dose and risk in dental diagnostic imaging with emphasis on dosimetry of CBCT. *Korean J Oral Maxillofac Radiol* 39: 175–184 (2009)
- LUDLOW J B: A manufacturer's role in reducing the dose of cone beam computed tomography examinations: effect of beam filtration. *Dentomaxillofac Radiol* 40: 115–122 (2011)
- LUDLOW J B, WALKER C: Assessment of phantom dosimetry and image quality of i-CAT FLX cone-beam computed tomography. *Am J Orthod Dentofacial Orthop* 144: 802–817 (2013)
- LUDLOW J B, TIMOTHY R, WALKER C, HUNTER R, BENAVIDES E, SAMUELSON B, SCHEKES J: Effective dose of dental CBCT – a meta-analysis of published data and additional data for nine CBCT units. *Dentomaxillofac Radiol* 44: 20140197 (2015)
- MÄNSSON L G: Methods for the evaluation of image quality: a review. *Radiat Prot Dosimetry* 90: 89–99 (2000)
- MARET D, TELMON, PETERS O A, LEPAGE B, TREIL J, INGLÈSE J M, PEYRE A, KAHN J L, SIXOU M: Effect of voxel size on the accuracy of 3D reconstructions with cone beam CT. *Dentomaxillofac Radiol* 41: 649–655 (2012)
- MARINE P M, STABIN M G, FERNALD M J, BRILL A B: Changes in radiation dose with variations in human anatomy: larger and smaller normal-stature adults. *J Nucl Med* 51: 806–811 (2010)
- MARSHALL G, SYKES A E: Systematic reviews: a guide for radiographers and other healthcare professionals. *Radiography* 17: 158–164 (2011)
- MARTIN C J, SHARP P F, SUTTON D G: Measurement of image quality in diagnostic radiology. *Appl Radiat Isot* 50: 21–38 (1999)
- MATHEWS J D, FORSYTHE A V, BRADY Z, BUTLER M W, GOERGEN S K, BYRNES G B, GILES G G, WALLACE A B, ANDERSON P R, GUIVER T A, MCGALE P, CAIN T M, DOWTY J G, BICKERSTAFFE A C, DARBY S C: Cancer risks in 680,000 people exposed to computed tomography scans in childhood or adolescence: data linkage study of 11 million Australians. *BMJ* 346: f2360 (2013)
- MATZEN L H, CHRISTENSEN J, HINTZE H, SCHOU S, WENZEL A: Diagnostic accuracy of panoramic radiography, stereo-scanography and cone beam CT for assessment of mandibular third molars before surgery. *Acta Odontol Scan* 71: 1391–1398 (2013)
- MATZEN L H, WENZEL A: Efficacy of CBCT for assessment of impacted mandibular third molars: a review – based on a hierarchical model of evidence. *Dentomaxillofac Radiol* 44: 20140189 (2015)
- MEADS C A, DAVENPORT C F: Quality assessment of diagnostic before-after studies: development of methodology in the context of a systematic review. *BMC Med Res Methodol* 9: 3 (2009)
- MELO S L, BORTOLUZZI E A, ABREU M, CORREA L, CORREA M: Diagnostic ability of a cone-beam computed tomography scan to assess longitudinal root fractures in prosthetically treated teeth. *J Endod* 36: 1879–1882 (2010)
- MILEMAN P A, VAN DEN HOUT W B: Evidence-based diagnosis and clinical decision making. *Dentomaxillofac Radiol* 38: 1–10 (2009)
- MORANT J J, SALVADO M, HERNANDES-GIRON I, CASANOVAS R, ORTRGA R, CALZADO A: Dosimetry and image quality of iCat FLX cone-beam computed tomography. *Am J Orthod Dentofacial Orthop* 144: 802–817 (2013)
- MORI S, ENDO M, NISHIZAWA K, TSUNOO T, AOYAMA T, FUJIWARA H, MURASE K: Enlarged longitudinal dose profiles in cone-beam CT and the need for modified dosimetry. *Med Phys* 32: 1061–1069 (2005)
- MOTA DE ALMEIDA F J, KNUTSSIN K, FLYGARE L: The effect of cone beam CT (CBCT) on therapeutic decision-making in endodontics. *Dentomaxillofac Radiol* 43: 20130137 (2014)
- MOTA DE ALMEIDA F J, KNUTSSIN K, FLYGARE L: The impact of cone beam computed tomography on the choice of endodontic diagnosis. *Int Endod* 48: 564–572 (2015)
- MOYNIHAN R, DOUST J, HENEY D: Preventing overdiagnosis: how to stop harming the healthy. *BMJ* 344: e3502 (2012)
- MOZZO E, PROCACCI C, TACCONI A, MARTINI P T, ANDREIS I A: A new volumetric CT machine for dental imaging based on the cone-beam technique preliminary results. *Eur Radiol* 8: 1558–1564 (1998)
- NATIONAL COUNCIL ON RADIATION PROTECTION AND MEASUREMENTS: NCRP Report No. 145. Radiation Protection in Dentistry www.ncrppublications.org/Reports/145 (2005)
- NATIONAL RESEARCH COUNCIL OF THE NATIONAL ACADEMIES: Health Risks from Exposure to Low Levels of Ionizing Radiation: BEIR VI1 (Washington DC: The National Academies Press) <https://doi.org/10.17226/11340> (2006)
- NEMTOI A, CZINK C, HABA D, GAHLTEINER A: Cone beam CT: a current overview of devices. *Dentomaxillofac Radiol* 42: 20120443 (2013)
- NEVES F S, VASCONCELOS T V, VAZ S L, FREITAS D Q, HAITER-NETO F: Evaluation of reconstructed images with different voxel sizes of acquisition in the diagnosis of simulated external root resorption using cone beam computed tomography. *Int Endod J* 45: 234–239 (2012)
- NIKOLIC-JAKOBA N, SPIN-NETO R, WENZEL A: Cone-Beam Computed Tomography for Detection of Intrabony and Furcation Defects: A Systematic Review Based on a Hierarchical Model for Diagnostic Efficacy. *J Periodontol* 87: 630–644 (2016)
- NOFFKE C E, FARMAN A G, NEL S, NZIMA N: Guidelines for the safe use of dental and maxillofacial CBCT: a review with recommendations for South Africa. *SADJ* 66: 264–266 (2011)
- PAPADAKIS A E, PERISINAKIS K, DAMILAKIS J: Automatic exposure control in pediatric and adult multi-detector CT examinations: a phantom study on dose reduction and image quality. *Med Phys* 35(10): 4567–4576 (2008)
- PARASHAR V, WHAITES E, MONSOUR P, CHAUDHRY J, GEIST J R: Cone beam computed tomography in dental education: a survey of US, UK, and Australian dental schools. *Dent Educ* 76: 1443–1447 (2012)
- PARSA A, IBRAHIM N, HASSAN B, MOTRONI A, VAN DER STELT P, WISMEIJER D: Influence of cone beam CT scanning parameters on grey value measurements at an implant site. *Dentomaxillofac Radiol* 42:79884780 (2013)
- PATEL S, DAWOOD A, MANNOCCI F, WILSON R, PITT FORD T: Detection of periapical bone defects in human jaws using cone beam computed tomography and intraoral radiography. *Int Endod J* 42: 507–515 (2009)

- PATEL K, MANNOCCI F, PATEL S: The Assessment and Management of External Cervical Resorption with Periapical Radiographs and Cone-beam Computed Tomography: A Clinical Study. *J Endod* 42: 1345-1440 (2016)
- PAUWELS R, STAMATAKIS H, MANOUSARIDIS G, WALKER A, MICHIELSEN K, BOSMANS H, BOGAERTS R, JACOBS R, HORNER K, TSIKLAKIS K, SEDENTEXCT PROJECT CONSORTIUM: Development and applicability of a quality control phantom for dental cone beam CT. *J Appl Clin Med Phys* 12: 245-260 (2011)
- PAUWELS R, BEINSBERGER J, COLLAERT B, THEODORAKU C, ROGERS J, WALKER A, COCKMARTIN L, BOSMANS H, JACOBS R, BOGAERTS R, HORNER K, SEDENTEXCT PROJECT CONSORTIUM: Effective dose range for dental cone beam computed tomography scanners. *Eur J Radiol* 81: 267-271 (2012a)
- PAUWELS R: Optimization of cone beam computed tomography for dentomaxillofacial applications. Dissertation of University of Leuven (2012b)
- PAUWELS R, THEODORAKOU C, WALKER A, BOSMANS H, JACOBS R, HORNER K, BOGAERTS R, SEDENTEXCT PROJECT CONSORTIUM: Dose distribution for dental cone beam CT and its implications for defining a dose index. *Dentomaxillofac Radiol* 41: 583-593 (2012c)
- PAUWELS R, BEINSBERGER J, STAMATAKIS H, TSIKLAKIS K, WALKER A, BOSMANS H, BOGAERTS R, JACOBS R, HORNER K, SEDENTEXCT PROJECT CONSORTIUM: Comparison of spatial and contrast resolution for cone-beam computed tomography scanners. *Oral Surg Oral Med Oral Pathol Oral Radiol* 114: 127-135 (2012d)
- PAUWELS R, STAMATAKIS H, BOSMANS H, BOGAERTS R, JACOBS R, HORNER K, TSIKLAKIS K, SEDENTEXCT PROJECT CONSORTIUM: Quantification of metal artefacts on cone beam computed tomography images. *Clin Oral Implants Res* A100: 91-94 (2013)
- PAUWELS R, COCKMARTIN L, IVANAUSKAITE D, URBONIENE A, GAVAL S, DONTA C, TSIKLAKIS K, JACOBS R, BOSMANS H, BOGAERTS R, HORNER K, SEDENTEXCT PROJECT CONSORTIUM: Estimating cancer risk from dental cone-beam CT exposure based on skin dosimetry. *Phys Med Biol* 59: 3877-3891 (2014a)
- PAUWELS R, SILKOSESSAK O, JACOBS R, BOGAERTS R, BOSMANS H, PANMEKIATE S: A pragmatic approach to determine the optimal kVp in cone-beam CT: balancing contrast-to-noise ratio and radiation dose. *Dentomaxillofac Radiol* 20140059 (2014b)
- PAUWELS R, ARAKI K, SIEWERDSEN J H, THONGVIGITMANEE S S: Technical aspects of dental CBCT: state of the art. *Dentomaxillofac Radiol* 44: 20140224 (2015a)
- PAUWELS R, SEYNAEVE L, HENRIQUES J C, DE OLIVEIRA-SANTOS C, SOUZA P C, WESTPHALEN F H, RUBIRABULLEN I R, RIBEIRO-ROTTA R F, ROCKENBACH M I, HAITER-NETO F, PITTAYAPAT P, BOSMANS H, BOGAERTS R, JACOBS R: Optimization of dental cone-beam CT exposures through mAs reduction. *Dentomaxillofac Radiol* 44: 20150108 (2015b)
- PEARCE M S, SALOTTI J A, LITTLE M P, MCHUGH K, LEE C, KIM K P, HOWE N L, RONCKERS C M, RAJARAMAN P, CRAFT A W, PARKER L, DE GONZÁLEZ A B: Radiation exposure from CT scans in childhood and subsequent risk of leukaemia and brain tumours: a retrospective cohort study. *Lancet* 380: 499-505 (2012)
- PETERSEN L, CHRISTENSEN J, OLSEN K, WENZEL A: Image and surgery-related costs comparing cone beam CT and panoramic imaging before removal of impacted mandibular third molars. *Dentomaxillofac Radiol* 43: 20140001 (2014)
- PETERSEN L B, MATZEN L H, OLSEN K, VAETH M, WENZEL A: Economic implications of routine CBCT examination before surgical intervention of the lower third molar in the Danish population. *Dentomaxillofac Radiol* 44: 20140406 (2015)
- PETERSEN L B, VAETH M, WENZEL A: Neurosensoric disturbances after surgical removal of the mandibular third molar based on rather panoramic imaging or cone beam CT scanning: A randomized controlled trial (RCT). *Dentomaxillofac Radiol* 45: 20150224 (2016)
- PETERSSON A, AXELSSON S, DAVIDSON T, FRISK F, HAKEBERG M, KVIST T, NORLUND A, MEJÅRE I, PORTENIER I, SANDBERG H, TRANÆUS S, BERGENHOLTZ G: Radiological diagnosis of periapical bone tissue lesions in endodontics: a systematic review. *Int Endod J* 45: 783-801 (2012)
- POPE O, SATHORN C, PARASHOS P: Comparative Investigation of Cone-beam Computed Tomography and Periapical Radiography in the Diagnosis of a Healthy Periapex. *J Endod* 40: 360-365 (2014)
- PRESTON D L, RON E, TOKUOKA S, FUNAMOTO S, NISHI M, SODA M, MABUCHI K, KODAMA K: Solid cancer incidence in atomic bomb survivors 1958-1998. *Radiat Res* 168: 1-64 (2007)
- QIAO J, WANG S, DUAN J, ZHANG Y, QIU Y, SUN C, LIU D: The accuracy of cone beam computed tomography in assessing maxillary molar furcation involvement. *J Clin Periodontol* 41: 269-274 (2014)
- QU X M, LI G, LUDLOW J B, ZHANG Z Y, MA X C: Effective radiation dose of ProMax 3D cone-beam computerized tomography scanner with different protocols. *Oral Surg Oral Med Oral Pathol Oral Radiol Endod* 110: 770-776 (2010)
- QU X, LI G, ZHANG Z, MA X: Thyroid shields for radiation dose reduction during cone beam computed tomography scanning for different oral and maxillofacial regions. *Eur J Radiol* 81: 376-380 (2012)
- ROBB R A: Dynamic spatial reconstructor: an X-ray video fluoroscopic CT scanner for dynamic volume imaging of moving organs. *IEEE Trans Med Imaging* 1: 22-33 (1982)
- ROBERTS J A, DRAGE N A, DAVIES J, THOMAS D W: Effective dose from cone beam CT examinations in dentistry. *Br J Radiol* 82: 35-40 (2009)
- RODRÍGUEZ G, ABELLA F, DURÁN-SINDREU F, PATEL S, ROIG M: Influence of cone beam tomography in clinical decision making among specialists. *J Endod* 43: 194-199 (2017)
- RENTON T, DAWOOD A, SHAH A, SEARSON L, YILMAZ Z: Post-implant neuropathy of the trigeminal nerve. A case series. *Br Dent* 212: e17 (2012)
- ROEDER F, WACHTLIN D, SCHULTZE R: Necessity of 3D visualization for the removal of lower wisdom teeth: required sample size to prove non-inferiority of panoramic radiography compared to CBCT. *Clin Oral Investig* 16: 699-706 (2012)
- ROOD J P, SHEBAB B A: The radiological prediction of inferior alveolar nerve injury during third molar surgery. *Br J Oral Maxillofac Surg* 28(1): 20-25 (1990)
- ROSEN E, TASCHIERI S, DEL FABBRO M, BEITLITUM I, TSEIS I: The Diagnostic Efficacy of Cone-beam Computed Tomography in Endodontics: A Systematic Review and Analysis by a Hierarchical Model of Efficacy. *J Endod* 41: 1008-1014 (2015)
- SCARFE W C, FARMAN A G: What is cone beam and how does it work? *Dent Clin Am* 52: 707-730 (2008)
- SCHULZE D, HEILAND M, THURMAN H, ADAM G: Radiation exposure during midfacial imaging using 4 and 16-slice computed tomography: cone beam computed tomography systems and conventional tomography. *Dentomaxillofac Radiol* 33: 83-86 (2004)
- SCHULZE R, HEIL U, GROSS D, BRUELLMANN D D, DRANISCHNIKOW E, SCHWANECKE U, SCHOEMER E: Artefacts in CBCT; a review. *Dentomaxillofac Radiol* 40: 265-273 (2011)
- SHELLEY A M, BRUNTON P, HORNER K: Subjective Image Quality Assessment of Cross Sectional Imaging Methods for the Symphyseal Region of the Mandible Prior to Dental Implant Placement. *J Dent* 39: 764-770 (2011)
- SHELLEY A M, FERRERO A, BRUNTON P, GOODWIN M, HORNER K: The impact of CBCT imaging when placing dental implants in the anterior edentulous mandible: a before-after study. *Dentomaxillofac Radiol* 44: 20140316 (2015)
- SIEGEL M J, SCHMIDT B, BRADLEY D, SUES C, HILDEBOLT C: Radiation dose and image quality in pediatric CT: Effect of technical factors and phantom size and shape. *Radiology* 233: 515-522 (2004)
- SPIN-NETO R, GOTTFREDSSEN E, WENZEL A: Impact of voxel size variation on CBCT-based diagnostic outcomes in dentistry: a systematic review. *J Digit Imaging* 26: 813-820 (2013)
- SPIN-NETO R, MATZEN L H, SCHRÖPP L, GOTTFREDSSEN E, WENZEL A: Movement characteristics in young patients and the impact on image quality: Dentomaxillofac Radiol 45: 20150426 (2016)
- STRATIS A, ZHANG G, LOPEZ-RENDON X, JACOBS R, BOGAERTS R, BOSMANS H: Customisation of a Monte Carlo dosimetry tool for dental cone-beam CT systems. *Radiat Prot Dosimetry* 169: 378-85 (2016)
- SUOMALAINEN A, KILJUNEN T, KASER Y, PELTOLA J, KORTESNIEMI M: Dosimetry and image quality of four dental cone beam computed tomography scanners compared with multislice computed tomography scanners. *Dentomaxillofac Radiol* 38: 367-378 (2009)
- SUR J, SEKI K, KOIZUMI H, NAKAJIMA K, OKANO T: Effects of tube current on cone-beam computerized tomography image quality for presurgical implant planning in vitro. *Oral Surg Oral Med Oral Pathol Oral Radiol* 110: e29-33 (2010)
- TAPIOVAARA M: Review of relationships between physical measurements and user evaluation of image quality. *Radiat Prot Dosimetry* 129: 244-248 (2008)
- THEODORAKU C, WALKER A, HORNER K, PAUWELS R, BOGAERTS R, JACOBS R, SEDENTEXCT PROJECT CONSORTIUM: Estimation of paediatric organ and effective doses from dental cone beam CT using anthropomorphic phantoms. *Br J Radiol* 85: 153-160 (2012)
- TSIKLAKIS K, DONTA C, GAVALA S, KARAYIANNI K, KAMENOPOLLOU V, HOURDAKIS C J: Dose reduction in maxillofacial imaging using low dose Cone Beam CT. *Eur J Radiol* 56: 413-417 (2005)
- TYNDALL D A, PRICE J B, TETRADIS S, GANZ S D, HILDEBOLT C, SCARFE W C: American Academy of Oral and Maxillofacial Radiology. Position statement of the American Academy of Oral and Maxillofacial Radiology on selection criteria for the use of radiology in dental implantology with emphasis on cone beam computed tomography. *Oral Surg Oral Med Oral Pathol Oral Radiol* 113: 817-826 (2012)
- TUBIANA M, FEINENDEGEN L E, YANG C, KAMINSKI J M: The linear no-threshold relationship is inconsistent with radiation biologic and experimental data. *Radiology* 251: 13-22 (2009)
- VAN GOMPEL G, VAN SLAMBROUCK K, DEFRISE M, BATENBURG K J, DE MEY J, SIBBERS J, NUYTS J: Iterative correction of beam hardening artifacts in CT. *Med Phys* 38: S36 (2011)
- VENSKUTONIS T, PLOTINO G, JUODZBALYS G, MICKEVIČIENE L: The importance of cone-beam computed tomography in the management of endodontic problems: A review of the literature. *J Endod* 40: 1895-1901 (2014)
- WALTER C, WEIGER R, DIETRICH T, LANG N P, ZITZMANN N U: Does three-dimensional imaging offer a financial benefit for treating maxillary molars with furcation involvement? A pilot clinical case series. *Clin Oral Implants Res* 23: 351-358 (2012)
- WALTRICK K B, NUNES DE ABREU M J, CORRÊA M, ZASTROW M D, DUTRA V D: Accuracy of linear measurements and visibility of the mandibular canal of cone-beam computed tomography images with different voxel sizes: an in vitro study. *J Periodontol* 84: 68-77 (2013)

- WANG G, VANNIER M W, CHENG P C: Iterative X-ray cone-beam tomography for metal artefact reduction and local region reconstruction. *Microsc Microanal* 5: 58–65 (1999)
- WATANABE H, HONDA E, TETSUMURA A, KURABAYASHI T: A comparative study for spatial resolution and subjective image characteristics of a multi-slice CT and a cone-beam CT for dental use. *Eur J Radiol* 77: 397–402 (2011)
- WHITE S C, SCARFE W C, SCHULZE R K W, LURIE A G, DOUGLASS J M, FARMAN A G, LAW C S, LEVIN M D, SAUER R A, VALACHOVIC R W, ZELLER G G, GOSKE M J: The Image Gently in Dentistry campaign: promotion of responsible use of maxillofacial radiology in dentistry for children. *Oral Surg Oral Med Oral Pathol Oral Radiol* 118: 257–261 (2014)
- WHITE S C, PHAROAH M J: *Oral Radiology. Principles and Interpretation*, 7th Edition, St. Louis, Mosby (2013)
- YADAV S, PALO L, MAHDIAN M, UPADHYAY M, TADINA-DA A: Diagnostic accuracy of 2 cone-beam computed tomography protocols for detecting arthritic changes in temporomandibular joints. *Am J Orthod Dentofacial Orthop* 147: 339–344 (2015)
- YU L, LIUX, LENG S, KOFLER J M, RAMIREZ-GIRALDO J C, QU M, CHRISTNER J, FLETCHER J G, MCCOLLOUGH C H: Radiation dose reduction in computed tomography: techniques and future perspective. *Imaging Med* 1: 65–68 (2009)
- ZHANG G, MARSHALL N, BOGAERTS R, JACOBS R, BOSMANS H: Monte Carlo modelling for dose assessment in cone beam CT for oral and maxillofacial applications. *Med Phys* 40: 072103 (2013)
- ZIJDERVELD S A, VAN DEN BERGH J P, SCHULTEN E A, TEN BRUGGENKATE C M: Anatomical and surgical findings and complications in 100 consecutive maxillary sinus floor elevation procedures. *J Oral Maxillofac Surg* 66: 1426–1438 (2008)