Cone Beam Computed Tomography
radiation dose and image quality assessments

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The long and winding road...

Lennon & McCartney

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Abstract

Diagnostic radiology has undergone profound changes in the last 30 years. New technologies are available to the dental field, cone beam computed tomography (CBCT) as one of the most important. CBCT is a catch-all term for a technology comprising a variety of machines differing in many respects: patient positioning, volume size (FOV), radiation quality, image capturing and reconstruction, image resolution and radiation dose. When new technology is introduced one must make sure that diagnostic accuracy is better or at least as good as the one it can be expected to replace. The CBCT brand tested was two versions of Accuitomo (Morita, Japan): 3D Accuitomo with an image intensifier as detector, FOV 3 cm x 4 cm and 3D Accuitomo FPD with a flat panel detector, FOVs 4 cm x 4 cm and 6 cm x 6 cm.

The 3D Accuitomo was compared with intra-oral radiography for endodontic diagnosis in 35 patients with 46 teeth analyzed, of which 41 were endodontically treated. Three observers assessed the images by consensus. The result showed that CBCT imaging was superior with a higher number of teeth diagnosed with periapical lesions (42 vs 32 teeth).

When evaluating 3D Accuitomo examinations in the posterior mandible in 30 patients, visibility of marginal bone crest and mandibular canal, important anatomic structures for implant planning, was high with good observer agreement among seven observers.

Radiographic techniques have to be evaluated concerning radiation dose, which requires well-defined and easy-to-use methods. Two methods: CT dose index (CTDI), prevailing method for CT units, and dose-area product (DAP) were evaluated for calculating effective dose (*E*) for both units. An asymmetric dose distribution was revealed when a clinical situation was simulated. Hence, the CTDI method was not applicable for these units with small FOVs. Based on DAP values from 90 patient examinations effective dose was estimated for three diagnostic tasks: implant planning in posterior mandible and examinations of impacted lower third molars and retained upper cuspids. It varied between 11-77 μSv.

Radiation dose should be evaluated together with image quality. Images of a skull phantom were obtained with both units varying tube voltage, tube current, degree of rotation and FOVs. Seven observers assessed subjective image quality using a six-point rating scale for two diagnostic tasks: periapical diagnosis and implant planning in the posterior part of the jaws. Intra-observer agreement was good and inter-observer agreement moderate. Periapical diagnosis was found to, regardless of jaw, require higher exposure parameters compared to implant planning. Implant planning in the lower jaw required higher exposure parameters compared to upper jaw. Substantial dose reduction could be made without loss of diagnostic information by using a rotation of 180°, in particular implant planning in upper jaw.

CBCT with small FOVs was found to be well-suited for periapical diagnosis and implant planning. The CTDI method is not applicable estimating effective dose for these units. Based on DAP values effective dose varied between 11-77 μSv (ICRP 60, 1991) in a retrospectively selected patient material. Adaptation of exposure parameters to diagnostic task can give substantial dose reduction.

Keywords: Cone beam computed tomography, anatomic landmarks, dose-area product, image quality, implant planning, periapical diagnosis, radiation dosimetry.

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Preface

The thesis is based on the following papers, which will be referred to in the text by their Roman numerals (I – IV):

I Lofthag-Hansen S, Huumonen S, Gröndahl K, Gröndahl H-G.
Limited cone-beam CT and intraoral radiography for the diagnosis of periapical pathology
Oral Surg Oral Med Oral Pathol Oral Radiol Endod 2007; 103: 114-19

II Lofthag-Hansen S, Gröndahl K, Ekestubbe A
Cone-beam CT for preoperative implant planning in the posterior mandible: visibility of anatomic landmarks
Clin Implant Dent Relat Res. 2009; 11: 246-55

III Lofthag-Hansen S, Thilander-Klang A, Ekestubbe A, Helmrot E, Gröndahl K.
Calculating effective dose on a cone beam computed tomography device: 3D Accuitomo and 3D Accuitomo FPD
Dentomaxillofac Radiol 2008; 37: 72–79

IV Sara Lofthag-Hansen, Anne Thilander-Klang, Kerstin Gröndahl
Evaluation of subjective image quality in relation to diagnostic task for cone beam computed tomography with different fields of view
Eur J Radiol 2010; doi:10.1016/j.ejrad.2010.09.018

Introduction

Diagnostic radiology has undergone profound changes in the last 30 years. New technologies have been developed and are becoming readily available also to the dental field. Development of hardware and software has allowed applications of new methods for dentomaxillofacial diagnosis and treatment planning as well as prosthetic and surgical treatment. Cone beam computed tomography (CBCT) might be one of the most important developments in dental radiology over the years.

The first prototype scanner for CBCT was developed and described already in 1982 for angiographic applications (Robb 1982). For dentomaxillofacial use a CBCT scanner was developed in the late 1990s, and since the very first report (Mozzo et al. 1998) the CBCT technique has gained great popularity in dentistry. The first commercial CBCT unit, available in Europe in 2001, was NewTom 9000 (Quantitative Radiology, Verona, Italy), that had a design similar to conventional computed tomography (CT) with a supine patient position during examination. The unit scanned the entire maxillofacial region with a volume of 15 cm x 15 cm and a complete 360° rotation for data acquisition. The detector was an image intensifier coupled with a solid-state charge couple device (CCD) camera. At the same time, a limited volume CBCT system, scanning a cylindrical volume with a diameter of 4 cm, was under development. This prototype, called Ortho-CT, was created by Arai and co-workers (1999) and based on the Scanora stand (Soredex Corp., Helsinki, Finland) with the patient in a sitting position during the examination. In 2000, actual construction of this CBCT device was transferred to J. Morita MFG. Corp. (Kyoto, Japan) where the 3DX limited CBCT was made ready for commercial use. In 2002, it was introduced to the European market under the name 3D Accuitomo and a year later, in March 2003, a 3D Accuitomo unit was installed at the Clinic of Oral and Maxillofacial Radiology, Public Dental Health, Göteborg, Sweden (Fig.1). It was equipped with an image intensifier connected to a CCD-camera as detector. The X-ray field size was 3 cm x 4 cm in the rotation centre and the reproduced volume thus corresponded to a cylinder of 3 cm in height and 4 cm in diameter. In August 2005, the 3D Accuitomo was replaced by a newer version, 3D Accuitomo FPD, in which a flat panel detector is used instead of an image intensifier and a CCD-camera. In this model, it is possible to choose between an X-ray field size of either 4 cm x 4 cm or 6 cm x 6 cm with reproduced volumes corresponding in size. In both versions the X-ray exposure is continuous. Table 1 gives the technical specification of the two scanners.

Figure 1. Patient positioned in the 3D Accuitomo FPD.

Today, CBCT is a catch-all term for a technology comprising a variety of machines differing from each other in many respects. The development has been fast and the name of the technique has varied *e.g.*, cone beam CT, limited cone beam CT, local cone beam CT, digital volume tomography (DVT), volumetric CT and volumetric tomography. The first manufacturers with the brands NewTom 9000 and 3D Accuitomo now have several new generations of scanners on the market along as do several other manufacturers. Depending on the brand the patient is in a seated, standing or supine position during the examination. The approach taken by different CBCT manufacturers in setting exposure factors is quite different. The simplest method to choose is the one where tube voltage (kV) and tube current (mA) are established by the manufacturer and hence, not to be varied from patient to patient *e.g.*, i-CAT (Imaging Sciences International, Hatfield, PA, USA) and NewTom 3G. Since these values must be sufficient for adults they will result in unnecessarily high exposures for children. For other brands *e.g.*, CB MercuRay (America, Twinsburg, OH, USA) and all versions of Accuitomo it is up to the operator to determine optimal kV- and mA-values. The X-ray exposure varies between machines in that it can be either continuous or pulsed (*e.g.*, i-CAT has a pulsed X-ray exposure), also the so-called field of view, the FOV

Table 1. Technical specification of the CBCT-scanners 3D Accuitomo and 3D Accuitomo FPD

Manufacturer	J. Morita MFG. Corp., Kyoto, Japan	
Model	3D Accuitomo	3D Accuitomo FPD
Patient positioning	seated	seated
Tube voltage (kV)	60-80 (1 kV step)	60-80 (1 kV step)
Tube current (mA)	1-10 (0.1 mA step)	1-10 (0.1mA step)
Radiation source	continuous	continuous
Rotation	180°, 360°	180°, 360°
Projections per rotation	≈ 300, 560	≈ 300, 560
Exposure time/Scan Time (s)	9 s (180°) and 17 s (360°)	9 s (180°) and 17.5 s (360°)
Scanned volume dimensions	3 cm x 4 cm	4 cm x 4 cm 6 cm x 6 cm
Detector type	Image intensifier – CCD camera	Flat panel
Voxel size (x, y, z)	0.125 mm x 0.125 mm x 0.125 mm	0.125 mm x 0.125 mm x 0.125 mm
Spatial resolution	2 lp/mm	2 lp/mm
Slice thickness (mm)	0.125 - 2	0.125 - 2
Gray scale depth	8 bit	12 bit
Field of View (FOV)	3 cm x 4 cm	4 cm x 4 cm 6 cm x 6 cm

(the height and diameter of the imaged volume) varies between brands. Some allow the FOV to be selected to suit the purpose of the examination, small fields for dental imaging to large fields for maxillofacial examinations. Consequently, as shown by *e.g.*, Ludlow & Ivanovic (2008) the radiation dose varies.

The CBCT imaging is accomplished by a synchronous rotation of an X-ray source and detector round the region of interest. The X-ray source and detector are placed on either side of a circular gantry, horizontally placed for seated and standing patients and vertically for patients in the supine position. CBCT scanners use a collimated narrow cone-shaped X-ray beam instead of a wider fan shaped beam resulting in a more limited FOV in the axial dimension than in conventional CT (Scarfe & Farman 2008). Image data is recorded in a single rotation varying between 200° and 360°. For some brands there is an option of choosing between a full-scan and a half-scan rotation. During the rotation multiple, from 150 to more than 600, sequential planar projection images are acquired. This series of projection images is referred to as raw data or projection data. The next stage, referred to as the reconstruction stage, consists of relating the collected images to each other to create a volumetric data set. This volumetric data set is presented as primary images on the monitor reconstructed in three orthogonal planes (axial, coronal and sagittal) at a default slice thickness. New reconstructions in all planes and with different slice thickness are easily performed. Earlier scanners employed an image intensifier with a charge couple device (CCD) camera as detector, some CBCT units still employ this technique, while flat panel detectors (FPD) have substituted the image intensifier and CCD technology in others. The most common flat panel configuration consists of a cesium iodide scintillator applied to a thin film transistor made of amorphous silicon (Scarfe & Farman 2008).

The advancement during the last 10 years in flat panel detectors, improved computing power and the relatively low power requirement of the X-ray-tube in connection with images well suited for evaluation of calcified structures, like bone tissue and teeth (high contrast structures), has facilitated the rapid arrival of marketable CBCT scanners for operating in dental offices. Further, advantage for the CBCT scanners is the design to encounter some of the disadvantages of conventional CT, which is more expensive and requires a considerable amount of space. Furthermore, lower radiation dose compared to conventional CT. The radiation dose and availability for conventional CT have been limiting factors to its usage to complex craniofacial problems.

When new technology is being introduced one must make certain that it is indeed better, or at least as good as, than the technology it is expected to replace. Månsson (2000) has made a very important statement: “It is easy to be blinded by new technology, much harder to know with certainty that the new technique is any good”. It is therefore important that relevant evaluation studies are being performed and that these are made before the technique in question becomes clinically implemented. This has not been the case concerning the CBCT technique, a fate it shares with most new diagnostic X-ray techniques. The implementation has by far preceded thorough evaluations, a fact that can be seen from the large number of papers dealing with the CBCT technique in dentomaxillofacial imaging. Especially in orthodontic diagnosis CBCT scanners with large imaging fields have become a substitute for panoramic and cephalometric images (Farman et al. 2005, Kau et al. 2005, Müssig et al. 2005) even though no studies have shown any changes in treatment outcome as a result of the new technology.

Fryback (1983) and Fryback & Thornbury (1991) suggested that the efficacy of imaging technologies, in particular new ones, should be evaluated at different levels with the most basic being on a technical level and the most advanced being a societal level. The intermediate levels deal with efficacy of diagnostic accuracy and diagnostic thinking, therapeutic efficacy and patient outcome efficacy. In the literature, studies on technical efficacy and diagnostic efficacy dominate. This is also the case for the CBCT technique.

De Vos and co-workers (2009) reviewed the literature on CBCT imaging of the oral and maxillofacial region. The search period covered a time period from 1998 to December 2007 and included 380 papers. They found 177 papers to be clinically relevant of which 86 dealt with patients, 65 related to technique, 16 to radiation dose and 26 were synopsis articles. Papers could be relevant to more than one group and thus, included in several groups. The review showed that CBCT was used in oral and maxillofacial surgery and orthodontics for numerous clinical applications, particular due to its low cost, easy accessibility and low radiation dose compared with multi-slice CT (MSCT). Further, the review found four papers related to endodontics and eleven to implantology (of which six concerned implant planning) of clinical interest. The 65 scientific papers, relating to technique, included CBCT imaging *in vitro* (*e.g.*, human cadavers, head phantoms, anatomical specimens, extracted teeth, geometrical objects) to evaluate its performance, features and usefulness. Twenty-eight papers evaluated the accuracy of linear measurements. Ten papers reported objective evaluation of the image quality (*e.g.*, resolution, distortion, noise), while subjective evaluation of image quality was dealt with in 23 papers (*e.g.*, overall anatomic image performance, specific diagnostic capability). Further, the results showed that there was a lack of evidence-based data on the radiation dose for CBCT imaging.

Radiographic imaging methods in dentomaxillofacial radiology

There are several techniques available in dentomaxillofacial radiology, with intra-oral and panoramic radiography being the two basic ones. The very first intra-oral radiograph was taken already in 1896, soon after the discovery of X-radiation by W C Röntgen and it has been the prevailing technique ever since. Intra-oral radiography provides 2D images with a high spatial resolution in the order of 20 line pairs per millimetre (lp/mm) and often the only technique required. Intra-oral radiographs can be divided into three categories: periapical, bite-wing and occlusal projections. For periapical and bite-wing radiographs the paralleling technique is to be used as it will give the least possible amount of distortion and anatomical noise.

Panoramic radiography, also a 2D imaging technique, was introduced into the market in the early 1960s. The technique produces a single tomographic image that includes both the maxillary and mandibular dental arches and their supporting structures. The resolution of panoramic images, approximately 5 lp/mm, is sufficient for many purposes but inferior to that obtained by intra-oral radiography. In addition to panoramic views, computer-controlled multimodality machines like the Scanora and Cranex Tome units (Soredex Corp., Helsinki, Finland), introduced in the 1980s and 1990s, can produce spiral conventional tomographic images from many areas of the jawbones in different planes. Other extra-oral images are cephalograms, mainly used for orthodontic assessments. All these conventional imaging methods are now available in digital formats in addition to the film-based.

In the 1970s, the development of conventional CT revolutionized diagnostic radiology, in particular medical radiology. This technique utilizes a rotating fan beam of X-rays, a corresponding sector of detectors and a computer to reconstruct *e.g.*, cross-sectional images. Continuing technological developments, such as spiral scanning and multi-slice scanners, have improved both the speed and quality with which images are obtained. Conventional CT also represents one of the earliest forms of digital X-ray imaging. It has also become increasingly used in dento-maxillofacial radiology, notably for pre-implant examinations, tumour diagnosis and maxillofacial traumata evaluations.

Radiographic techniques for endodontic diagnosis

The radiographic examination is an essential part of endodontic management, from initial diagnosis to monitoring treatment results. Intra-oral periapical radiography has been, and still is, the prevailing technique used to establish whether periapical disease is present or not. In intra-oral radiography the 3D object is compressed into a 2D image from which the observer has to mentally recreate the three dimensions. This can be difficult even when more than a single radiograph is obtained. Of particular concern is the complex background of bone pattern that a periapical lesion has to be detected against. Bender & Seltzer (1961 a, b) and Schwarz & Foster (1971), among others, have shown that the size of the periapical lesion is often underestimated in intra-oral radiographs. For treatment planning purposes more information is often required, such as the number of roots and root canals, and which root that is affected. When periapical surgery is needed, knowledge about the relation between root apices with their lesions and neighbouring anatomic structures is essential. The relation to the maxillary sinus and the mandibular canal is also of importance. Hence, the intra-oral radiographic technique has sometimes to be supplemented with other radiographic techniques.

It has been demonstrated that periapical bone lesions, particular in premolar and molar regions, are better detected using spiral conventional tomography than intra-oral periapical radiography (Tammisalo et al. 1993). For special occasions conventional CT may give important information as in re-treatment decisions when considering root fillings in maxillary molars (Huumonen et al. 2006).

Velvart and co-workers (2001) noted that the relation between a periapical lesion and the mandibular canal, as studied before endodontic surgery, could be reliably assessed by means of conventional CT. The radiation dose should, however, be considered individually. Further, the conventional CT technique is not readily available in the dental office.

The development of CBCT is without doubt a significant step towards improved pre- and postoperative diagnosis in the endodontic field as a complement to intra-oral radiography and as a replacement to conventional tomography and in particular conventional CT. An advantage with the CBCT technique is that regions, or teeth, to be compared over time do not need to be examined with exactly the same projection geometry, as is the case in intra-oral radiography. Similarity between images can be achieved *post hoc* both in terms of geometry and contrast.

Given the limitations of intra-oral periapical radiography and the cost in form of radiation dose for conventional CT, we considered it of interest to assess whether and how information obtained by means of CBCT differs from that obtained from intra-oral periapical radiography. That was the incitement to *Study I*.

Radiographic techniques for preoperative implant planning

Depending upon the results of the clinical examination, the primary radiographic examination can be made with a combination of intra-oral and panoramic radiography or by one or the other. Assessment of the location of the mandibular canal and maxillary sinus, as well as the angulation of the alveolar process and, in particular, the bone volume is often a prerequisite for an appropriate treatment planning. Consequently, the radiographic examination in many patients has to include cross-sectional tomography. So far, two main groups of tomographic techniques have been used: conventional tomography and conventional CT. The opinion of what technique to choose differs among both oral radiologists and clinicians who will install the implants. According to *e.g.*, Clark and co-workers (1990), Ekestubbe & Gröndahl (1993) and Frederiksen (1995) conventional tomography is to be preferred in the partial dentate patient. Conventional tomography, as applied for dental purposes, underwent a profound development in the end of the 1980s when X-ray machines dedicated for examination of the jawbones entered the market. With units such as Scanora, later followed by Cranex Tome from the same company, a comprehensive pre-implant examination of a patient could be made in the unit. By means of these multimodal units, conventional spiral tomography could be performed of limited regions selected from a panoramic view of the entire jaw or part of it. A disadvantage with conventional tomography is the occasional degradation of the image quality as a result of disturbing ghost shadows from surrounding structures (Curry et al. 1990). Conventional CT is widely used for pre-implant tomography, often because other techniques are not available (Ekestubbe et al. 1997) and is easily performed but can also be associated with high radiation doses (Frederiksen et al. 1995, Dula et al. 1996, 1997, BouSerhal et al. 2002). The radiation doses can, however, be significantly reduced, although still being higher than from conventional tomography, by adhering to so-called low-dose protocols which are well suited for examinations where the primary interest lies in depicting bony structures (Ekestubbe et al. 1996, 1999).

Guidelines for preoperative radiographic examinations were published in 2000 by the American Academy of Oral and Maxillofacial Radiology (Tyndall & Brooks) and in 2002 by European Association for Osseointegration (Harris et al.). Those guidelines do not include the CBCT technique because in the early 2000s it was a fairly new and not widely spread technique. Based on the number of published scientific papers about the value of the CBCT technique for preoperative implant planning one can conclude that it is now considered an important technique in this respect (Guerrero et al. 2006, Ludlow et al. 2007, Suomalainen et al. 2008, Veyre-Goulet et al. 2008). However, none of these studies have taken the influence of the observer into account although it is well known from studies in medical and dental radiology that various observers may arrive at different results when examining the same radiographs. It is also known that one and the same observer can contradict his or hers own findings at re-examinations (Lusted 1968). This was the incitement to *Study II*.

Radiation dose

According to Thilander-Klang & Helmrot (2010) there are a number of ways to determine the effective dose (E). They also describe *e.g.*, entrance surface skin dose (ESD), organ dose (D_T), air kerma-area product (KAP, P_{KA}), dose-area product (DAP), energy imparted (ε), computed tomography dose index by volume ($CTDI_{vol}$), CT air kerma-length product (P_{KL}) and dose simulation programs. The determination of effective dose includes assumptions resulting in limitations and uncertainties. To be able to estimate the effective dose it is necessary to know the mean absorbed doses to the tissues and organs, which are difficult to measure in patient examinations. They are therefore made on anthropomorphic phantoms. In addition, the effective dose is only valid for a group of individuals and was initially intended to estimate the risk of irradiation of a population working with radiation and not of patients. The use of effective dose has nevertheless often been used for estimating risks in radiological examinations.

The traditional way of estimating effective dose is by determining the absorbed dose to the irradiated organs using thermoluminecent dosimeters (TLDs). The procedure is laborious and time-consuming and no standards exist regarding the number and location of measuring points. Hence, as reported by Ludlow and co-workers (2006), the reproducibility of the TLD technique can be low.

For dose measurements in diagnostic radiology it is important to have well-defined and easy-to-use methods. Helmrot & Alm Carlsson (2005) have shown that use of a DAP-meter that measures KAP, P_{KA} and DAP is a useful tool in radiological quality control programs. According to Thilander-Klang & Helmrot (2010) the use of DAP for determining diagnostic standard dose (DSD) and dose reference level (DRL) may be a better choice than the effective dose.

The background to *Study III* was to evaluate whether an easy-to-use method, such as measuring the DAP value, is useful for assessment of effective dose for the CBCT units 3D Accuitomo and 3D Accuitomo FPD in addition to the CT dose index (CTDI) method, which is the dose estimation technique used for conventional CT units. Furthermore, the aim was to estimate the effective dose for three specific examinations commonly performed in dental radiology: preoperative implant planning in the posterior mandible and examinations of impacted lower third molars and retained upper cuspids.

Image quality

There is no general agreement as to what should be included in a discussion of image quality, nor is there an agreement what method to choose for its evaluation. According to Månsson (2000), methods for image quality assessments can be divided into four major groups: physical measurements, psychophysical measurements, evaluation of observer performance and, finally, evaluation of diagnostic performance. Physical measurements are used to evaluate imaging properties (X-ray equipment and detectors) as well as dosimetric characteristics of the radiographic procedure. Psychophysical measurements deal with the response of an observer to visual stimuli. Observer performance describes the ability of an observer to detect relevant features in hybrid images or in images obtained on phantoms. Hence, these three first methods do not evaluate the diagnosis of actual patients. The fourth, the diagnostic performance is focused on patient diagnosis in the clinic and comprises all aspects of performance evaluating methods ranging from simple preference studies to different visual grading methods and Receiver Operating Characteristic (ROC) analysis (Swets & Pickett 1982). According to Kundel (1979) images of highest diagnostic quality are those that enable the observer "to most accurately report diagnostically relevant structures and features".

Image quality versus radiation dose

An accepted ratio between radiation dose and image quality needs to be reached to follow the ALARA (As Low As Reasonably Achievable) principle (ICRP 26, 1977). This principle includes taking radiographs based on the patient's needs, determined by a thorough clinical examination after taking the history of the patient and the use of an appropriate radiographic technique with optimized exposure settings. Additionally, the use of properly trained and credential staff is to be stressed. The quality of an image can be related only to a specific diagnostic task and the image should convey enough information to allow a decision to be made with an acceptable degree of certainty. Previous studies have shown that low exposure settings used in conventional CT can achieve comparable information in head and neck imaging as higher settings (Cohnen et al. 2000, Sohaib et al. 2001, Gündoğdu et al. 2005). Further, Rustemeyer and co-workers (2004) evaluated helical conventional CT images obtained with constant tube voltage (120 kV) and with varying the tube current (50 mA and 165 mA). They found no significant difference in visibility of mandibular structures, such as cortical bone and bone pattern, as judged by eight radiologists. They claim that their tested low-dose protocol is expected to be in the same range for CBCT without specifying what CBCT brand they refer to. Ekestubbe and her co-workers (1999) found that conventional spiral tomograms (Scanora) were subjectively preferred by eight observers, six oral radiologists and two oral surgeons, over conventional multislice CT images (GE Hispeed Advantage CT scanner, General Electric Medical Systems, Paris, France) when evaluating the mandibular canal and the marginal bone crest, structures important for preoperative implant planning in the mandible. The radiographic examinations were performed in 17 patients with an age range of 38 to 78 years. Further, their results showed that the mandibular canal was more frequently untraceable in high-dose (80 mAs) than in low-dose (40 mAs) CT images, but always depicted in conventional spiral tomograms. The studies performed with the CT technique using low-dose protocols was the incentive to *Study IV* with the purpose to compare image quality of images obtained with 3D Accuitomo and 3D Accuitomo FPD and the use of different exposure settings (kV, mA, degree of rotation) and different fields of view for two diagnostic tasks: periapical diagnosis and preoperative implant planning.

Aims

The aims of the four studies included in the present thesis were to:

- compare cone beam CT (3D Accuitomo) with intra-oral periapical radiography for the diagnosis of periapical pathology (*Study I*).

- evaluate visibility of the marginal bone crest and mandibular canal and agreement between observers in cone beam CT images (3D Accuitomo) (*Study II*).

- evaluate two methods, CT dose index (CTDI) and dose-area product (DAP), for estimation of effective dose for cone beam CT (3D Accuitomo and 3D Accuitomo FPD) (*Study III*).

- estimate effective dose from cone beam CT (3D Accuitomo and 3D Accuitomo FPD) for three commonly used examinations in dental radiology: implant planning in the posterior mandible and examination of impacted lower third molars and retained upper cuspids (*Study III*).

- study the influence of different exposure parameters on the subjective image quality of cone beam CT images (3D Accuitomo and 3D Accuitomo FPD) for two diagnostic tasks: periapical diagnosis and preoperative implant planning (*Study IV*).

Study I

Limited cone-beam CT and intraoral radiography for the diagnosis of periapical pathology

Materials and methods

Maxillary premolars and molars and mandibular molars with suspected periapical lesions examined with periapical radiography and a CBCT technique were retrospectively selected. Among the 35 patients included 46 teeth were identified: one tooth in 25 patients, two teeth in nine patients and three teeth in one patient (Table 2).

In each tooth region two intra-oral radiographs had been obtained with a dental X-ray machine (Oralix DC, Gendex Corporation, Milwaukee, WI, USA) using a paralleling technique with a horizontal angle difference of about 10° and F-speed film (Kodak Insight, Eastman Kodak, Rochester, NY, USA). The operating parameters were 65 kV and 7.5 mA with a focus-object distance of 22 cm. The radiographs were evaluated against a light box with the aid of an X-ray viewer (2x magnification).

For the CBCT examinations 3D Accuitomo with a volume of 3 cm x 4 cm was used. Operating parameters were 80 kV, between 2-4 mA and a rotation of 360°. From the reconstructed volume sagittal slices (1 mm thick) were placed parallel to the axis of the alveolar process. New slices for each specific root were not obtained. The images were analyzed at a Dell workstation (PWS 350) equipped with an 18-inch Dell monitor and a Triniton tube (resolution 1024 x 768 pixels).

Together, three oral radiologists first evaluated the intra-oral radiographs and after two weeks the Accuitomo images. In a later session the two techniques were evaluated side-by-side noting if additional information was provided by the Accuitomo images and if so, what kind of new information that was obtained. In case of disagreement the observers had to reach consensus.

Results

Of the 46 teeth analyzed, 41 were endodontically treated. Among the latter, 23 had a post in one or more root canals. In the periapical radiographs, two premolars were assessed to have two roots whereas only one root was seen in the Accuitomo images. Three maxillary molars were assessed as having two roots while three were found in the Accuitomo images. With respect to root canals, 124 were found in the periapical radiographs and 12 more in the Accuitomo images (seven in maxillary and five in mandibular molars). Among the 46 teeth, 32 were found with periapical lesions in both techniques, and an additional 10 teeth with periapical lesions were found in the Accuitomo images (Table 2).

Table 2. Distribution of tooth types (n) evaluated and number of teeth with periapical lesion diagnosed per technique

Jaw	*Tooth type (n)*	*Periapical radiographs*	*3D Accuitomo*
Maxilla	Premolar (9)	8	8
	1st molar (18)	14	17
	2nd molar (7)	4	7
Mandible	1st molar (7)	5	5
	2nd molar (5)	1	5
Total	(46)	32	42

Most of the undetected lesions were small. However, three large lesions involving the entire alveolar process with perforation of the cortical bone plates and expansion into the maxillary sinus were undetected in the periapical radiographs. As regards individual roots, 53 lesions were found in both techniques, and 33 more roots were found to have lesions in the Accuitomo images. The maxillary sinus was assessed as being situated between the buccal and palatal roots of seven teeth in periapical radiographs and at an additional four teeth in the Accuitomo images.

When both techniques were interpreted together the observers found that the Accuitomo images in 70% of the cases provided additional, clinically relevant information *e.g.*, about root anatomy, location and size of the lesion, relation lesion-maxillary sinus, not found in the periapical radiographs.

Conclusions

We conclude that in selected cases *e.g.*, when there is no detectable pathology in periapical radiographs although clinical tests and symptoms so indicate or when endodontic surgery is planned for multi-rooted teeth, additional radiographic examination using a 3D technique, such as the 3D Accuitomo, should be considered.

Study II

Cone-beam CT for preoperative implant planning in the posterior mandible: visibility of anatomic landmarks

Materials and methods

Thirty consecutive patients referred for implant planning and examined with 3D Accuitomo were retrospectively selected. The inclusion criteria were implant planning in one side of the mandible with loss of second premolar and molars (on actual side) and the mental foramen depicted in the examined volume. The group comprised 22 women and eight men with a mean age of 69 years (range 48-88 years). Operating parameters were 75 or 80 kV, between 2-6 mA and a rotation of 360°. The reconstructed volume was placed parallel with the axis of the alveolar process and the inferior border of the mandibular canal or the mandibular base if the canal was not depicted clearly. Depending on the angle between the mandibular canal or the mandibular base and the horizontal plane during exposure, the images will be displayed in different magnifications. In our study, the magnification varied between 3.0 and 4.7 times. Axial, cross-sectional and sagittal slices (1 mm thick) were transferred to PACS (Sectra-Imtec AB, Linköping, Sweden).

The images were presented to seven observers, all oral radiologists, on a 20-inch monochromatic monitor (RadiForce G20 2 MP, Eizo Nanao Corp., Ishikawa, Japan) with a resolution of 1600 x 1200 pixels. The screen was divided into four equal parts to enable a presentation of axial, cross-sectional and sagittal images in separate stacks. At the evaluations each case was presented with a predetermined cross-sectional image, approximately 1 cm posterior of the mental foramen, while the sagittal and axial stacks showed the position of the mental foramen (Fig. 2). The observers evaluated independently the visibility of the marginal bone crest and the mandibular canal in two sessions. When performing the first evaluation (visibility test) the observers were not informed of the second evaluation (marking test).

At the visibility test the observers assessed the visibility of the two anatomic structures according to a 3-point rating scale (Clearly visible, Probably visible and Invisible). If the structures were not considered "Clearly visible" the observers had to use more cross-sectional and/or sagittal and axial images and make a new decision of one or both anatomic structures. After two weeks a new evaluation was performed. The observers had now to mark the marginal bone crest and the centre of the mandibular canal with a cross (Fig. 3). If the observer found the

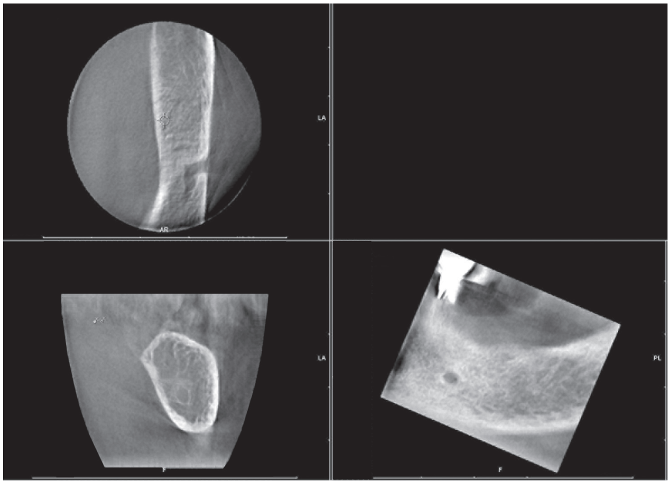


Figure 2. The 3D Accuitomo images displayed on the monitor when starting the two viewing sessions.

structure/s difficult to identify, he/she had to use more images from the separate stacks to be able to mark the two structures. One of the authors recorded if and which stack/s was/were used. If the marking was done in the predetermined cross-sectional image without any help of other images the evaluated structures were considered as “Clearly visible”.

Results

The visibility of the marginal bone crest was better than the visibility of the mandibular canal for each of the seven observers. All observers agreed on the marginal bone crest to be “Clearly visible” in 22 of the 30 images in the predetermined cross-sectional image at the visibility test. The corresponding number for the mandibular canal was ten. For all observers together there were a total of 19 decisions as “Probably visible” for the marginal bone crest, when using more images eight of these decisions were changed to “Clearly visible”. For the mandibular canal a more complex pattern was found (Table 3). In seven cases none of the observers asked for more images than the predetermined cross-sectional image.

In the marking test a higher score of decision level “Clearly visible” for the marginal bone crest was noted for all observers, while the opposite was found for the mandibular canal. When marking the mandibular canal no observer asked for more images in five cases. A large agreement among the observers was found when marking the marginal bone crest. Disagreement of >1 mm was found in only two of the 30 cases, while there was a disagreement of >1 mm in nine cases for the mandibular canal. Figure 3 shows the variation between the marks in the cross-sectional images among the observers in some of the cases (for complete presentation see Paper II, Fig. 2).

Table 3. The change of the score "Probably visible" and "Invisible" at the visibility test for the mandibular canal based on more images per observer (A-G)

		Mandibular Canal	
Observer	*Clearly*	← *Probably* →	← *Invisible*
A	*1*	←———————	———┐
	8	← **12** *1*	← **3**
B	*1*	←———————	———┐
	2	← **11** →	*1* **2**
C	*5*	←———————	———┐
	4	← **5**	**6**
D	*4*	← **6**	-
E	*1*	←———————	———┐
	7	← **8** *1*	← **2**
F	*1*	←———————	———┐
	3	← **6** →	*1* **6**
		3	←—┘
G	*5*	← **11** *2*	← **3**

The use of other images than the predetermined cross-sectional image varied among the observers depending on the anatomic structure evaluated. More images were used for decisions involving the mandibular canal, especially when the task was to mark its position.

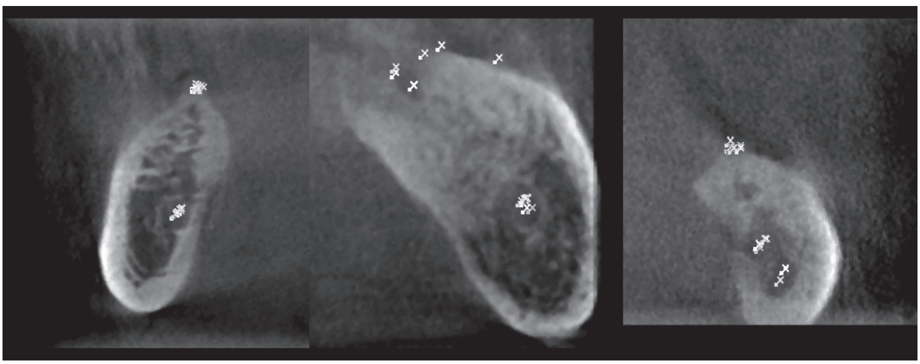


Figure 3. Variation between marks in three cross-sectional images among the seven observers.

Conclusions

With 3D Accuitomo the visibility of the marginal bone crest and the mandibular canal as well as the observer agreement on their location were high. Hence, it can be recommended as the tomographic technique to use when necessary for implant planning in the posterior mandible.

Study III

Calculating effective dose on a cone beam computed tomography device: 3D Accuitomo and 3D Accuitomo FPD

Materials and methods

This study was performed using 3D Accuitomo (volume 3 cm x 4 cm) and 3D Accuitomo FPD (volumes 4 cm x 4 cm and 6 cm x 6 cm). The 3D Accuitomo has an X-ray image intensifier and a CCD-camera as detector and 3D Accuitomo FPD has a flat panel detector. When evaluating the CTDI (CT dose index) method a CT head dose phantom made of PerspexTM (Ø 16 cm) and a 100 mm pencil ionization chamber connected to an electrometer were used (Fig. 4a).
The phantom has five holes, one in the centre and four evenly distributed 1 cm from the periphery. The pencil ionization chamber was placed and exposed in each of the five positions with the axis of rotation of the X-ray beam in the centre of the phantom. Exposure parameters were 60-80 kV and 1-10 mA. To simulate imaging a patient, the CT head dose phantom was repositioned so that the rotation centre became placed in a region corresponding to the upper left cuspid. When the patient examination was simulated the dose distribution was found to be asymmetric. Consequently, a correct $CTDI_{vol}$, which is necessary for further calculations with the CTDI method and based on a symmetrical dose distribution, could not be determined and we decided not to pursue this method for the patient examinations. Evaluating the DAP (dose-area product) method a plane-parallel transmission ionization chamber (DAP-meter) covering the entire X-ray beam connected to an electrometer was used (Fig.4b). The exposure parameters varied for the three volumes (Table 4). Corrections were made for the radiation quality used and the decrease in dose to the patient caused by the

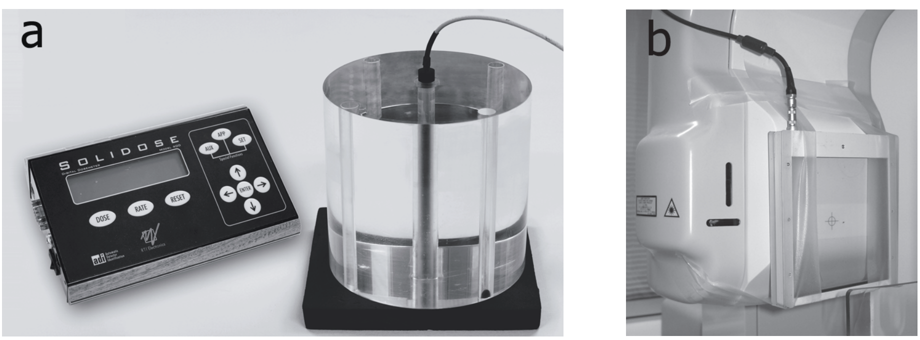


Figure 4. a) CT head dose phantom and pencil ionization chamber used with the CTDI method.
b) Plane-parallel transmission ionization chamber (DAP-meter) for measuring dose-area product.

attenuation of the ionization chamber itself. All measurements were repeated two or three times the same day to control the precision of the measuring instruments. In addition, re-measurements were performed one month and six months later for the 6 cm x 6 cm volume.

Table 4. Exposure parameters used for dose-area product (DAP) measurements

kV \ mA	1	2	3	4	5	6	7	8	9	10
60										40x40
70										40x40
75		40x40		40x40		40x40		40x40		40x40
80	30x40	40x40, 60x60	30x40			40x40, 30x40, 60x60				40x40, 60x60

30x40 mm 40x40 mm 60x60 mm

For determination of effective dose (E) from DAP values a conversion factor (E_{DAP}) has to be used. As the Accuitomo examination exposes the same radiosensitive organs and has similar projection geometry as panoramic radiography the conversion factor (0.08 mSv per Gy cm^2) established for the latter technique was used (Helmrot & Alm Carlsson 2005). Accordingly, effective dose was calculated from the formula $E=DAP \times E_{DAP}$. From 30 consecutive patients for each diagnostic task, implant planning in posterior mandible and examinations of impacted lower third molars and retained upper cuspids, exposure settings and volumes used were collected from a register kept for Accuitomo examinations at the clinic. Based on these data DAP values were calculated and effective doses based on ICRP 60 (1991) were estimated.

Results

The variation between repeated measurements was negligible for both $CTDI_{vol}$ and DAP measurements repeated the same day and for those repeated after several months. With the axis of rotation in the centre of the CTDI phantom the dose distribution was almost symmetrical with its highest value in the centre position. A difference of 2.7% was found when using the reference settings given by the manufacturer in the operation instructions.

The DAP value increased with higher kV- and mA-values as well as with larger volumes. With constant kV- and mA-values the DAP value was three times higher for the 6 cm x 6 cm volume than for the 3 cm x 4 cm volume, which is the same relation as that between exposed areas. For each mA-value (2, 4, 6, 8 or 10 mA) a change of 10 kV increased the DAP value by about 30-40%.

Table 5 shows the exposure parameters, volumes, DAP values and effective doses for the three selected types of examinations with the two Accuitomo units. In the consecutive patient examinations the DAP values ranged from 140 to 967 mGy cm^2 resulting in effective doses between 11 and 77 µSv. When comparing effective doses calculated from DAP values with those from a study made with TLD measurements and the 3D Accuitomo (Iwai et al. 2000) operating at the same exposure parameters, it was found that the DAP method gave the same dose value in the upper incisor area but lower in the mandibular molar area.

Table 5. Most commonly used exposure parameters in three specified regions and corresponding dose-are product (DAP) value and effective dose according to ICRP 60 (1991)

Region	*Volume size (mm x mm)*	*Tube voltage (kV)*	*Tube current (mA)*	*DAP value (mGy cm^2)*	*Effective dose (µSv)*
Upper jaw					
Cuspid	30 x 40	80	5.0–6.0	263–316	21–25
	40 x 40	75	4.0–5.0	260–325	21–26
	60 x 60	75	4.5–5.5	645–788	52–63
Lower jaw					
Second premolar–first molar	30 x 40	75–80	3.0–6.0	140–316	11–25
	40 x 40	75	4.0–6.0	260–390	21–31
	60 x 60	75	5.0–6.0	716–859	57–69
Lower jaw					
Third molar	30 x 40	75–80	3.0–6.5	140–342	11–27
	40 x 40	75–80	4.0–5.0	260–366	21–29
	60 x 60	75–80	4.5–6.0	645–967	52–77

Conclusions

We found the DAP method, but not the CTDI method, to be useful for estimating the effective dose for the two versions of 3D Accuitomo studied. It is an easy-to-use method and in a future a DAP-meter could be made an integral part of a CBCT unit. Both 3D Accuitomo versions reproduce small volumes and thus, in contrast to CBCT units reproducing large volumes, the rotation centre will vary with the region of interest. Consequently, the dose distribution will be asymmetric. Hence, the conversion factor, E_{DAP}, may over- or underestimate the effective dose in different regions. Perhaps different conversion factors, or a mean of different factors, have to be used for different dental regions and radiographic techniques. Further studies on which conversion factors to use in dental radiology are needed. The effective dose was found to be proportional to the volume, thus doses for the 3D Accuitomo FPD will be 1.3 (4 cm x 4 cm) and 3 times (6 cm x 6 cm) higher than for 3D Accuitomo (3 cm x 4 cm) given the same exposure parameters.

Study IV

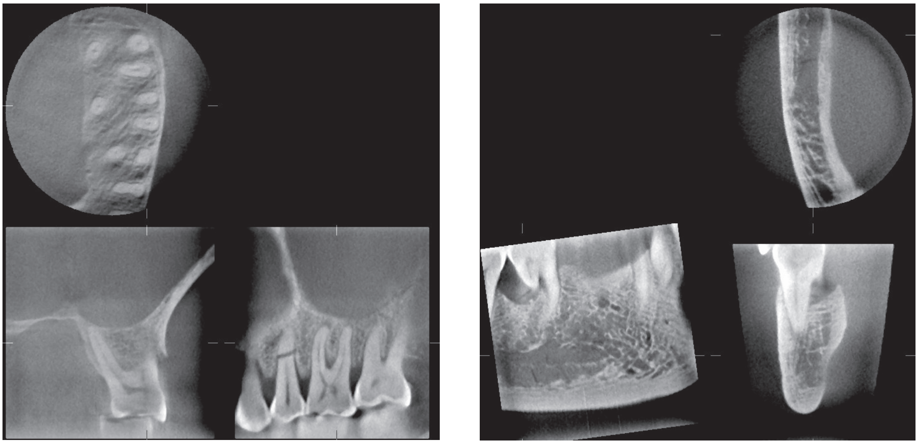
Evaluation of subjective image quality in relation to diagnostic task for cone beam computed tomography with different fields of view

Materials and methods

The 3D Accuitomo (3 cm x 4 cm) and 3D Accuitomo FPD (4 cm x 4 cm and 6 cm x 6 cm) were used in this study. Examinations of the posterior part of the maxilla and the mandible were performed on a dry skull embedded in acrylic material to simulate soft tissue. The skull phantom was placed with the hard palate horizontally. The exposure parameters used were all combinations of 60, 65, 70, 75, 80 kV and 2, 4, 6, 8, 10 mA with a rotation of both 180° and 360°. In both jaws the examined volumes were reconstructed parallel with the axis of the alveolar process and, further, in the mandible parallel with the mandibular base.

Of the totally 300 examinations, 27 were excluded due to too low signal to the detector. For the evaluation of intra-observer agreement 60 randomly selected duplicates (10 for each volume and jaw) were added to the study. Each combination (without scanning data) was presented to seven observers with a predetermined image displaying the area of interest in axial, cross-sectional and sagittal views and slice thickness 1 mm, and shown in a random order for each volume, jaw and observer. The observers, all with four to six years of experience of working with the CBCT technique, assessed independently the image quality on a 6-point rating scale (Totally agree, Agree, Slightly agree, Slightly disagree, Disagree and Totally disagree) for two diagnostic tasks, periapical diagnosis and implant planning.

The predetermined sets of images were shown on a 20-inch monochrome monitor (resolution of 1600 x 1200 pixels) by the soft-copy viewer ViewDEX 2.0 (Viewer for Digital Evaluation of X-ray images) (Håkansson et al. 2010). The observers were allowed to adjust brightness and contrast settings and to use zooming. Regardless of volume, a presetting of 1:1 was used. To each set of images there were five statements concerning image quality: three related to visibility of anatomic structures while two related to diagnostic task (periapical diagnosis and implant planning) (Fig. 5). The three anatomic structures were thought to make the observers aware of structures and features important for the chosen diagnostic tasks. The results are only based on the two statements related to the diagnostic tasks.



Upper jaw	Lower jaw
1. Clear inferior border of maxillary sinus	1. Clear mandibular canal
2. Clear delineation of outer cortical bone plates	2. Clear marginal bone crest
3. Clear trabecular bone pattern	3. Clear trabecular bone pattern
4. Image quality sufficient for periapical diagnosis	4. Image quality sufficient for periapical diagnosis
5. Image quality sufficient for implant planning in the posterior maxilla	5. Image quality sufficient for implant planning in the posterior mandible

Figure 5. Examples of images and corresponding statements from the evaluation sessions of upper and lower jaw, respectively.

The radiation dose to the skull phantom was determined using the air kerma-area product value (also called dose-area product, DAP). The DAP values (mGy cm^2) were measured using a plane-parallel transmission ionization chamber connected to an electrometer.

Statistical methods

Intra- and inter-observer agreements were calculated as weighted Kappa (κ_w). Stepwise logistic regression was used to select the best variable or combination of variables (DAP value, kV, mA, rotation, volume, jaw, diagnostic task) that predicted the decision levels "Totally agree" and "Agree" within all images. All comparisons applied two-sided test with 5% significance level.

Results

The DAP value for each combination is given in Table 6.

The intra-observer agreement presented as weighted Kappa was 0.74 for periapical diagnosis and 0.75 for implant planning, both corresponding to good agreement according to Altman (1991). The inter-observer agreement was 0.52, which corresponds to moderate agreement.

Table 6. Exposure parameters for the three FOVs and DAP values (mGy cm²) for rotation 360° and within brackets 180°. DAP values in italics indicate excluded examinations and ∗ only upper jaw

FOV 3x4

mA \ kV	60		65		70		75		80	
2	_60*_	(31)	73	(38)	85	(44)	96	(50)	107	(56)
4	121	(63)	145	(75)	170	(88)	192	(100)	215	(111)
6	181	(94)	218	(113)	255	(132)	288	(149)	322	(167)
8	242	(125)	291	(151)	339	(176)	384	(199)	429	(222)
10	302	(157)	363	(188)	424	(220)	480	(249)	537	(278)

FOV 4x4

mA \ kV	60		65		70		75		80	
2	_83_	_(43)_	_101_	_(52)_	_119*_	_(61)*_	_137*_	_(71)*_	154	_(79)*_
4	_165*_	_(85)*_	_201*_	_(104)*_	238	_(122)*_	274	(141)	308	(159)
6	_248*_	_(128)*_	302	(156)	356	(184)	411	(212)	462	(238)
8	331	_(171)*_	403	(208)	475	(245)	548	(283)	616	(318)
10	414	(213)	503	(259)	594	(306)	685	(353)	771	(397)

FOV 6x6

mA \ kV	60		65		70		75		80	
2	180	_(93)*_	219	_(113)*_	259	_(133)*_	299	_(154)*_	336	_(173)*_
4	361	(186)	439	(226)	518	(267)	598	(308)	672	(346)
6	541	(279)	658	(339)	777	(400)	896	(462)	1008	(520)
8	721	(372)	878	(452)	1036	(534)	1195	(616)	1344	(693)
10	901	(465)	1097	(566)	1295	(667)	1494	(770)	1680	(866)

Of all decisions (n=3 822) 50% were evaluated by all seven observers as having an image quality at either of the two highest decision levels ("Totally agree" and "Agree"). At decision levels "Totally agree" and "Agree" and selecting ≥6 observers the results showed that images obtained from higher exposure parameters, regardless of jaw, were chosen by the observers for periapical diagnosis than for implant planning (Tables 7 and 8). For implant planning there was a demand of higher exposure parameters for the lower jaw than for the upper (Tables 7 and 8). Noteworthy, is the large number of images obtained with a 180° rotation for which ≥6 observers totally agreed or agreed that they were sufficient for implant planning purposes, particularly in the upper jaw.

The results from stepwise logistic regression on all images showed that all variables were highly statistically significant for the decision levels "Totally agree" and "Agree" (Table 9). The overall ranking between the three volumes was 4 cm x 4 cm, 6 cm x 6 cm and 3 cm x 4 cm. Of all tested variables kV, mA and

Table 7. Exposure parameters in the upper jaw with inter-observer agreement of ≥6 observers at decision level "Totally agree" and "Agree". ○ indicates a rotation of 360°, ◗ a rotation of 180° and * lowest DAP value per volume and diagnostic task

FOV 3x4

Implant planning

mA \ kV	60	65	70	75	80
2					○*
4			○	○	○◗
6	○	○	○	○◗	○◗
8	○	○◗	○◗	○◗	○◗
10	○	○◗	○◗	○◗	○◗

Periapical diagnosis

mA \ kV	60	65	70	75	80
2					
4					
6				○*	○
8				○	○
10		○	○	○	○

FOV 4x4

Implant planning

mA \ kV	60	65	70	75	80
2					○
4			○	○◗*	○◗
6		○◗	◗	○◗	○◗
8	○	○◗	○◗	○◗	○◗
10	○	○◗	○◗	○◗	○◗

Periapical diagnosis

mA \ kV	60	65	70	75	80
2					
4					
6				○	○◗*
8				○◗	○◗
10			○◗	○◗	○◗

FOV 6x6

Implant planning

mA \ kV	60	65	70	75	80
2					
4				○◗*	○◗
6		○	○◗	○◗	○◗
8	○	○◗	○◗	○◗	○◗
10	○	○◗	○◗	○◗	○◗

Periapical diagnosis

mA \ kV	60	65	70	75	80
2					
4					
6					○
8			◗*	○◗	○◗
10				○◗	○◗

Table 8. Exposure parameters in the lower jaw with inter-observer agreement of ≥6 observers at decision level "Totally agree" and "Agree". ○ indicates a rotation of 360°, ◗ a rotation of 180° and * lowest DAP value per volume and diagnostic task

FOV 3x4

Implant planning

mA \ kV	60	65	70	75	80
2					
4				◗*	◗
6				◗	◗
8		◗	◗		
10		○	○◗	○	○◗

Periapical diagnosis

mA \ kV	60	65	70	75	80
2					
4					
6					
8					
10				○*	○

FOV 4x4

Implant planning

mA \ kV	60	65	70	75	80
2			○		
4				○	○
6			○	○◗*	○◗
8		○	○	○◗	○◗
10		○◗	○◗	○	○◗

Periapical diagnosis

mA \ kV	60	65	70	75	80
2					
4				○*	○
6			○	○	○
8			○	○◗	○◗
10		○◗	○◗		○◗

FOV 6x6

Implant planning

mA \ kV	60	65	70	75	80
2					
4					○
6		○	○	○	○◗*
8			○◗	○◗	○◗
10	○	○	○	○	○

Periapical diagnosis

mA \ kV	60	65	70	75	80
2					
4					○
6			○	○	○
8			○◗*	○◗	○◗
10		○	○	○◗	○◗

diagnostic task were found to be the ones most important when predicting the decision levels “Totally agree” and “Agree” with an area under the ROC-curve of 0.87. When all seven variables were included in the model the area under the ROC-curve increased to 0.90.

Table 9. Stepwise logistic regression on all images for decision level “Totally agree” and “Agree”
OR = Odds Ratio, CI = Confidence interval, Area under the ROC curve = 0.90
* Volume 3x4 has an image intensifier as detector, while volumes 4x4 and 6x6 have a flat panel detector

Parameter	OR	95% CI	p-value
DAP (per 100 mGy cm^2)	1.19	1.08 - 1.32	0.0009
mA (per 2 mA)	1.60	1.49 - 1.72	<0.0001
kV (per 5 kV)	1.20	1.18 - 1.22	<0.0001
Rotation (180 vs 360)	0.47	0.36 - 0.63	<0.0001
Volume* (3x4 vs 6x6)	0.72	0.46 - 1.12	<0.0001
Volume * (4x4 vs 6x6)	2.03	1.39 - 2.97	<0.0001
Jaw (upper vs lower)	2.45	2.04 - 2.93	<0.0001
Diagnosis (implant planning vs periapical diagnosis)	6.74	5.54 - 8.20	<0.0001

Conclusions

The observers requested higher exposure parameters, hence higher radiation dose expressed as DAP values, to reach an image quality at higher decision levels for periapical diagnosis compared to that requested for the diagnostic task implant planning. For implant planning higher exposure parameters were requested for the lower jaw.

The observed difference between the volumes can have different explanations. One is the use of image intensifier versus flat panel detector technology. Another is the difference in exposed volumes since the amount of scatter radiation increases as a function of volume. For the particular CBCT brand used in our study a 180° rotation was found to be sufficient for implant planning in the upper jaw. Hence, a substantial dose reduction can be achieved. The skull phantom used corresponds to a large male patient. Thus, lower exposure parameters, than found to be useful based on our results, can be recommended for females and children. In addition, the exposure settings have to be adjusted related to diagnostic task.

Discussion

This series of investigations indicates that the CBCT technique, at least when it is performed with small volumes, is associated with a high diagnostic value in dentomaxillofacial radiology.

Clinical studies are an obvious way to test the efficacy of new techniques. The validity of such studies depends on estimation of the ground truth and, according to Wenzel & Hintze (1999), preferably based on histological data. This, however, requires studies performed on cadaver phantoms, which will reduce the variety of both anatomic and pathological structures as the number of available specimens can be expected to be low. Further, clinical studies are both expensive and often time consuming and the technology they seek to monitor present moving targets. By the time the studies have been completed, the new technology has taken evolutionary steps forward. Alternatives to clinical studies are offered by laboratory investigations in form of physical measurements on imaging systems or components, such as spatial resolution, contrast and noise level. However, these approaches are challenged by the issue of how to relate these measures to the clinical performance of the systems. One way to solve the problem with clinical studies is to use a retrospective patient material, as in *Study I* and *Study II*. Using a retrospective patient material is not without problems as it is no guarantee that the image quality is optimal, but it might reflect an everyday use.

When evaluating new radiographic technologies the radiation dose has to be taken into account and reliable, easy-to-use methods have to be identified (*Study III*). Further, the radiation dose should be kept as low as possible and in balance with the image quality (*Study IV*). The degree of image quality might differ depending on the diagnostic task. Consequently, to evaluate the quality of radiographic imaging several aspects have to be taken into account, including the importance of the observers.

In *Study I*, intra-oral periapical radiography and a CBCT technique (3D Accuitomo) were evaluated by three oral radiologists, who had to reach consensus when deciding if a periapical lesion was present or not. The patient material (36 patients) was retrospectively selected from the first year after the installation of the CBCT unit in the clinic. Hence, one can expect that the image quality was not optimal. Still, the CBCT technique demonstrated a larger number of affected teeth, 42 teeth for the Accuitomo images compared to 32 teeth for the intra-oral images. Even large lesions were not detected in the intra-oral radiographs, a fact that is not surprising when knowing the limitation of the intra-oral technique as demonstrated by Bender & Seltzer (1961 a, b), Schwarz & Foster (1971) and others. Of the 46 teeth analyzed, 41 were endodontically treated, of which 23 had a post in one or more roots. According to White & Pharoah (2008) metallic restorations and, but to a less extent, root canal filling material cause bright or dark streaks in CBCT images. Loubele and co-workers (2008) found, when comparing multi-slice CT (MSCT) with four different CBCT scanners (3D Accuitomo, i-CAT, NewTom 3G, CB MercuRay), that metal artefacts were more disturbing in MSCT images than in CBCT images.

In periapical radiography, especially in the maxillary molar region, optimal irradiation geometry can be difficult to achieve because of *e.g.*, a low palatal vault. A necessary irradiation geometry with the X-ray beam coming too much from above results in superimposition of the maxillary zygomatic process and the zygomatic bone onto the roots as well as distorted images of the roots. Twenty-five of the analyzed 46 teeth were maxillary molars.

For the periapical radiographs F-speed film was used. If digital systems using sensors had been employed instead of film or image plates, the difference between the two tested techniques might have been even larger as the active image area in most sensors is smaller than that of film or image plates. A less optimal projection geometry is then necessary to capture the apices of the roots. Unlike film images, digital images can be manipulated to make them better suited for different diagnostic tasks. *In vitro*, it has been shown that observers were somewhat better in detecting lesions confined to the lamina dura and the cancellous bone when digital images were used as opposed to film images (Yokota et al. 1994). However, it is highly unlikely that such a difference would have had an influence on the present results, had digital sensors been used.

The CBCT technique produces undistorted 3D images in all three orthogonal planes, axial, coronal and sagittal and any planes in-between. In our study, however, new slices for each specific root were not reconstructed. Our results are consistent with other studies (Rigolone et al. 2003, Stavropoulos & Wenzel 2007, Estrela et al. 2008, Low et al. 2008, de Paula-Silva et al. 2009, Sogur et al. 2009).

Stavropoulos & Wenzel (2007) studied the accuracy of CBCT (NewTom 3G), intra-oral digital (Dixi2, Planmeca, Oy, Helsinki, Finland) and film radiography

(F-speed) for the detection of periapical lesions (lesion sizes 1 mm x 1 mm and 2 mm x 2 mm) created in an *ex vivo* study in pig jaws, and found that the NewTom 3G was statistically significantly better in terms of sensitivity (54%), positive (83%) and negative (45%) predictive values, and diagnostic accuracy (61%) when compared with digital intra-oral (23%, 70%, 35%, 39%) and film radiography (28%, 70%, 35%, 44%) except for positive predictive value. The specificity was similar for all three methods. No difference was found between the two intra-oral techniques. De Paula-Silva and co-workers (2009) also used an animal model to study the accuracy of periapical radiography (D-speed film) and CBCT scans (NewTom 3G) in diagnosing periapical lesions using histological findings as gold standard. Of 83 roots the periapical radiographs showed periapical lesions in 71% of the roots, the CBCT scans in 84% and while 93% were histologically diagnosed. Diagnostic accuracy was 0.78 for periapical radiography and 0.92 for CBCT. When studying accuracy of CBCT (3D Accuitomo XYZ Slice View Tomograph), panoramic and periapical radiography (F-speed film) for the detection of periapical lesions in 888 consecutive patients Estrela and co-workers (2008) used the diagnostic results from the CBCT images as the reference method (gold standard). They found that the prevalence of periapical lesions was significantly higher in the CBCT images and in 54.5% periapical lesions were correctly identified with periapical radiography and in 27.8% with panoramic radiography.

Also Low and co-workers (2008) compared periapical radiography (F-speed film) and CBCT (3 DX Accuitomo XYZ Tomograph) for diagnosis of posterior maxillary teeth of consecutive patients referred for apical surgery. The images were analyzed by two specialists (oral radiology and endodontics), who had to reach consensus in the interpretation of the radiographic findings. The material included 37 premolars and 37 molars. The CBCT images showed significantly more lesions (109 lesions), of which 34% were not detected with periapical radiography. Detecting lesions with the intra-oral technique was more difficult in second molars. They also point out other highlights with the CBCT technique, like additional findings seen in CBCT images including expansion of lesions into the maxillary sinus, sinus membrane thickening and missed root canals.

To summarize Study I supported by previously presented studies, it seems safe to conclude that CBCT is more sensitive in detecting periapical lesions than intra-oral radiography. For many reasons a 3D technique ought to be better than a 2D technique, anything else would be counter-intuitive.

Radiography is used to detect pathology *e.g.*, periapical lesions at remaining teeth in presumptive implant patients, but it also plays an important role in giving information about the bone height and its width and intended implant sites′ relation to vital anatomic structures such as the mandibular canal. To fulfill the objectives of the radiographic examination, the use of more sophisticated techniques than intra-oral and panoramic radiography is often needed. The results in *Study II* are based on 30 consecutive patients, retrospectively selected, examined with 3D Accuitomo for implant planning in the posterior mandible. The reason behind the decision to choose this particular region, the posterior mandible, as the test region was that many earlier studies testing a variety of radiographic techniques preceding the CBCT technique, such as conventional tomography (Gröndahl et al. 1991, Lindh et al. 1992, Ekestubbe & Gröndahl 1993, Kim & Park 1997, BouSerhal et al. 2001, Frei et al. 2004) and conventional CT (Ekestubbe et al. 1996, 1999), had chosen this particular region.

Among the 30 patients (mean age 69 years, range 48-88 years) 22 (73%) were women. As in *Study I* the CBCT unit used was 3D Accuitomo. Large agreement among the observers was observed when marking the marginal bone crest with a disagreement in only two cases, while a disagreement of the same magnitude, >1mm, was found in nine cases for the mandibular canal. There was a preference to use more cross-sectional images for both anatomic structures and for the two evaluations, visibility and marking tests. The seven observers might have been unwilling to make a decision on a single image knowing that more radiographic information was present, especially for the marking test, where their decisions were to be compared with those of the other observers in a more unmasked way. According to Lou and co-workers (2007) the reliability of the identification of different landmarks depends on numerous factors such as the clarity of the definition used to describe the landmarks to the observers, the image quality and the image contrast between adjacent anatomic structures.

In a clinical study of conventional spiral tomography, Ekestubbe & Gröndahl (1993) found the variation between observers measuring the distance between the highest point of the marginal bone crest and the upper border of the mandibular canal to be due to discrepancies in identifying the marginal bone crest. The difference between the observers in our study to identify the marginal bone crest might be caused by a misunderstanding. Some of the observers might have thought that the instruction was to mark the starting point for drilling of an implant site instead of marking the top of the bone crest. Regarding the mandibular canal, a misunderstanding cannot be expected as the observers were asked to mark the center of the canal. When marking the bone crest, all observers placed the mark within a diameter of <1mm in 28 of the 30 cases. For the mandibular canal, the corresponding number was 21 of the 30 cases. So, if the distances between the marked anatomic structures had been measured by our observers, the agreement between them should have been high in approximately 20 out of the 30 cases. This result can be compared to the results presented for conventional spiral tomography by Ekestubbe & Gröndahl (1993). They found that in no case out of 40 patients did all six observers agree on the measured distance between the marginal bone crest and the mandibular canal and the mean range between the observers was 3.3 mm (SD 2.3).

Suomalainen and her co-workers (2008) studied the accuracy of linear measurements using CBCT (3D Accuitomo) and conventional MSCT (GE LightSpeed Plus, General Electric Medical Systems) based on measurements on a dry mandible. The distance between the marginal bone crest and the mandibular canal was measured by two observers and compared to measurements performed with a slide gauge in microradiographs of 4 mm thick slices of the mandible. The measurement error showed significant differences between the methods studied (p=0.022), the measurement error was 4.7% for CBCT and 8.8% for MSCT. Further, Loubele and co-workers (2007) compared the buccolingual dimensions in the canine and premolar area with CBCT (3D Accuitomo) and conventional spiral tomography (Cranex Tome) on 25 dry mandibles. Measurements of the mandibles by means of a digital sliding caliper acted as gold standard and one observer performed all measurements twice. The intra-observer agreement was good and the caliper measurements were on average 0.23 mm (SD 0.49) and 0.34 mm (SD 0.90) larger than the CBCT and conventional spiral tomography measurements, respectively.

As a conclusion of Study II and above discussed studies it can be concluded that CBCT, and in particular 3D Accuitomo, is a reliable tool for implant planning measurements. A statement that is supported in many other studies evaluating other CBCT brands *e.g.*, PSR 9000 (Asahi Roentgen, Kyoto, Japan) (Kobayashi et al. 2004), NewTom 9000 (Veyre-Goulet et al. 2008) and Iluma (Imtec (3M) Ardmore, USA) (Kamburoğlu et al. 2009).

The radiation dose from CBCT imaging depends on the specific brand as well as the exposure parameters used. Considering the individual organs and tissues exposed by a CBCT technique working with large scanned volumes the doses will be greatest to the eye lenses, salivary glands and thyroid glands. When considering a large image field, the effective dose ranges from 44 to 50 µSv for some machines and up to 477 µSv for others (Ludlow et al. 2006). For a medium size volume it will be about 20 µSv (Hasimoto et al. 2003, Mah et al. 2003) and as low as 7-12 µSv for a 4 cm field of view (Iwai et al. 2000). The reported radiation dose for the CBCT technique is not consistent as both different dose quantities and methods have been used. For the CBCT unit 3D Accuitomo Iwai and co-workers (2000) reported effective dose from measurements with TLDs, while Hashimoto and co-workers (2003) reported skin dose measurements. Okano and co-workers (2009) have also reported effective dose based on TLD measurements for 3D Accuitomo and 3D Accuitomo FPD. The exposure settings used were 80 kV and 5 mA with a rotation of 360° and the effective doses were estimated to be about 18-66 µSv depending on imaging volume. These values are in the same range as the effective doses found in *Study III* based on DAP values when using the definition of effective dose from ICRP 60 (1991). Okano and co-workers did also estimate the effective doses according to the latest ICRP 103 (2008) recommendations and found the effective doses to be higher, in the range of 15-60%, because of the new weighting factors for the salivary glands and brain. Further, Suomalainen and her co-workers (2009), also using TLD measurements, reported effective doses for examinations of lower left third molar with 3D Accuitomo (FOV 3 cm x 4 cm) and 3D Accuitomo FPD (6 cm x 6 cm). Using their common clinical exposure parameters, 80 kV and 4 mA with a rotation of 360°, the effective doses were found to be 14 µSv and 63 µSv, respectively according to ICRP 60 (1991). This is in the same range as in *Study III*. When estimation of the effective dose was made with ICRP 103 (2008) they found the corresponding values to be 27 µSv and 166 µSv, respectively.

As pointed out in the *Introduction* the way to estimate the effective dose by measuring the mean absorbed dose to organs and tissues using TLDs is a laborious and time-consuming method without standards regarding the number and location of measuring points. Further, as has been pointed out by Ludlow and co-workers (2006) the reproducibility is low, especially apparent for those TLDs placed on the skin. Thilander-Klang & Helmrot (2010) have stated that the estimation of the effective dose can be associated with uncertainties of ± 40% or more, and they recommend that it should be used with care, an opinion also shared by Borrás & Huda (2010) and McCollough and her co-workers (2010).

We found in *Study III* that measurement of DAP was an easy method to use. A drawback of the DAP method will be an overestimation of the radiation dose to the patient when the X-ray beam at times exposes areas outside the patient. Further, there is not yet a general acceptance for what conversion factors to use in oral radiology should effective dose be estimated. However, the DAP value is a sufficient method for comparing radiation dose to patients from the same type of examinations, and in some cases also between different examination techniques. Helmrot & Thilander-Klang (2010) reported DAP values for different types of examinations in dentomaxillofacial radiology. They reported that one intra-oral radiograph (8-10 mGy cm^2) corresponds to approximately 1/8 of the DAP value for a panoramic radiograph (adult, 80 mGy cm^2). Further, an examination with 3D Accuitomo FPD with a FOV of 4 cm x 4 cm (350 mGy cm^2) corresponds to about 4-5 panoramic images. These patient doses have been recorded from examinations from over 200 dental X-ray machines, 32 panoramic units and 5 CBCT machines at different dental clinics in Sweden. Helmrot &

Thilander-Klang (2009, in Swedish) reported the DAP value for conventional spiral tomography using the Scanora unit to be in order of 250-390 mGy cm^2 for 4 tomograms covering an area of 16 mm (four 4-mm tomographic images).

With the very fast development in the CBCT field with the number of manufacturers and devices growing rapidly, there is a need to find an easy-to-use method to measure the radiation dose. In a review article, Kau and co-workers (2009) identified sixteen manufactures and twenty-three devices using the CBCT technology applied to the maxillofacial region. Cone beam CT imaging will continue to evolve rapidly and play an increasingly important role in dentistry. Hence, there is a high demand for easy techniques to evaluate these machines, both from radiation dose aspects but also from image quality aspects. The results from *Study III* shows that the DAP method can be a tool to compare CBCT brands regarding the radiation dose.

There are possibilities to reduce the radiation dose in CBCT imaging. However, some brands use fixed tube voltage (kV), tube current (mA) and exposure time, while other brands allow the operator to adjust these exposure parameters. Some brands permit the operator to collimate the beam to the region of interest. Some units produce pulsed exposure, which will reduce the dose to the patient, but it is a delicate task to balance the exposure with the read out of the detector (*e.g.* CCD-camera) as it only can register a limited number of images per second. Further, as pointed out by *e.g.*, Vandenberghe and co-workers (2007), there is a need to determine ideal exposure settings to optimize image quality and lower the radiation dose. The variables that can be modified kV, mA, FOV and degree of rotation for the optimization depend on unit. All these parameters are adjustable for the CBCT brand Accuitomo.

The results from *Study IV* showed that there was a difference between the three volumes examined, most likely due to different detectors - image intensifier versus flat panel detector - and imaged volume that influence the amount of scatter radiation. To lower the latter it is important to select the smallest FOV possible while continuing to provide adequate target-region coverage. Further, the results showed that a rotation of 180° was found to be sufficient for implant planning in the upper jaw, while higher exposure parameters were needed to achieve the same decision level for the lower jaw. This difference might be due to denser bone in the mandible with thicker cortical bone plates but also the presence of an important anatomic structure, the mandibular canal. Our observers were all well aware of the importance of accurate localization of the canal in implant planning and that unintentional penetration of it during surgical drilling as a result of its inaccurate localisation might cause permanent neurological complications. The results showed that the exposure parameters could be adjusted to the diagnostic task.

To reach an image quality at higher decision levels for periapical diagnosis the observers needed images taken with higher radiation doses expressed as higher DAP values. This demand is probably due to the fact that for periapical diagnosis more delicate anatomic structures, the lamina dura and the periodontal ligament space, are included in the decision if a lesion is present or not.

Subjective image quality has also been studied by Liang and co-workers (2010) testing CBCT and MSCT. They used one dry mandible placed in a plastic container and immersed in water to simulate soft tissue and then scanned with five CBCT scanners: NewTom 3G, 3D Accuitomo, i-CAT, Galileos (Sirona, Bensheim, Germany), Scanora 3D (Soredex, Tuusula, Finland) and one MSCT scanner (Somatom Sensation, Siemens, Erlangen, Germany). The cortical bone and the mandibular canal were included among the 11 anatomic structures studied. The results showed that the image quality of the five CBCT systems were comparable to that of MSCT and for one system, 3D Accuitomo, the overall image quality was superior.

Kwong and co-workers (2008) performed a study with CB MercuRay evaluating image quality varying tube voltage (100 and 120 kV), tube current (2, 5, 10 and 15 mA), with and without a copper filter and using three different FOVs. The study was performed with images from a fresh human cadaver head (FOV 6 and 9 inches, approximately 15 and 23 cm, respectively) and a dry skull (FOV 12 inches, approximately 30 cm). Images were obtained to resemble bite-wing and panoramic radiographs for the small and medium FOV, respectively and lateral cephalograms from the large FOV. A number of 30 observers evaluated each group of images, which were printed on glossy photo paper. The 16 images in each group were ranked from 1 to 16 with 1 to represent the best overall image quality and 16 the worst. They found it possible to lower the tube current settings and further, that the presence or absence of a copper filter and the tube voltage setting (100 or 120 kV) did not affect the overall image quality.

Sur and co-workers (2010) performed a study similar to ours. They also used 3D Accuitomo FPD when examining six human cadavers, both upper and lower jaws, with a FOV of 6 cm x 6 cm and a tube voltage of 80 kV. They varied the tube current (1, 2, 4 and 8 mA) for each specimen which was examined with both 180° and 360° of rotation. The images obtained at 8 mA in full-scan mode were used as gold standard with which all other images were compared. Five oral radiologists, using a 4-point rating scale, subjectively evaluated the visibility of anatomic landmarks associated with implant planning. An average score was calculated for each landmark. The images were evaluated with a slice thickness of 0.5 mm. The results showed that 4 mA images at full-scan mode could visualize the landmarks in the upper and lower jaws as good as the 8 mA images. Even 2 mA images obtained with 360° and 4 mA with 180° could be used for implant planning, while 1 mA images were unacceptable owing to a substantial degradation in image quality. In general, the landmarks in the lower jaw reached higher scores than for the upper jaw when comparing the same mA-value, which is a result that was not supported in our study.

Based on *Study IV* and supported the study by Sur and co-workers, it seems safe to conclude that in many patients significant dose reductions may be achieved without substantial loss of image quality by reducing exposure parameters and selecting half-scan mode. However, our study has shown that the exposure parameters and degree of rotation have to be selected depending on diagnostic task in order to fulfill the implications of the ALARA principle (ICRP 26, 1977). Because the study was performed on just one skull phantom a similar study in a clinical set-up would be necessary to confirm the results.

Regardless of technique evaluated it is not only the costs in radiation dose that has to be considered but also the monetary costs. The costs of CBCT equipment is relatively low, about €150,000 to €300,000. The economical aspect has not been investigated in our studies.

Visual grading of the reproduction of important anatomic structures for evaluating image quality in radiography has become an established method for several reasons (Båth & Månsson 2007). First of all, the validity of such studies can be assumed to be high since the quality criteria are based on clinical relevant structures and the normal anatomic background is included. Secondly, in special cases visual grading methods have been shown to agree with methods based on ROC analysis (Sund et al. 2000, Tingberg et al. 2000) and with calculations of physical image quality (Sandborg et al. 2000, 2001). This is important and validates in some way the assumption that the possibility to detect pathology correlates to the reproduction of anatomy. Third, visual grading studies are relatively easy to conduct. Fourth, the time consumption is moderate. Finally, this kind of studies does not require a gold standard.

The investigations included in this thesis are based on two diagnostic performance studies including retrospectively selected patient materials (*Study I* and *Study II*) and two phantom studies (*Study III* and *Study IV*), of which one was an observer performance study. Månsson (2000) distinguish between the terms observer performance and diagnostic performance. According to him observer performance should be used as the general term to describe the ability of a human observer to properly detect relevant image features (human or artificial, anatomic or pathological) in images, while diagnostic performance should be used when both detection and interpretation of clinical cases are carried out. Hence, phantom studies will by this definition be observer performance studies.

The observers used in our studies were formally trained oral radiologists or dentists, all with 4-6 years experience of working with the CBCT technique at an oral and maxillofacial radiology clinic. In *Study I* three observers evaluated the two studied techniques, while seven observers evaluated the CBCT images in *Study II* and *Study IV*. According to Swets & Pickett (1982) it is always better to add an observer than to have an observer read the images a second time, and in choosing between adding another observer or adding a number of cases the former choice has a better influence on the statistical power.

As pointed out in the *Introduction* new methods need to be evaluated before being implemented in the clinic. Fryback (1983) and Fryback & Thornbury (1991) have described a hierarchy of levels at which a method can be evaluated. At lower levels technical efficacy and diagnostic accuracy efficacy are evaluated. At the highest level the efficacy from a societal point of view is evaluated. Also Fineberg & Hiatt (1979) and Maisey & Hutton (1991) have categorized the evaluation of diagnostic methods in six levels: technical capacity, diagnostic accuracy, diagnostic impact, therapeutic impact, patient outcome, optimal usage (cost-benefit, cost-effectiveness). Their opinion is also that studies according to levels 3-6 are scarce. Regardless of what model described above, our studies concern the lower levels of the hierarchies. Nevertheless, a method with poor efficacy on a lower level may have no value at higher ones.

There is a need to develop selection criteria for obtaining CBCT images. There are currently no broadly accepted guidelines for identifying patients who are likely to benefit by having a CBCT examination. Guidance on the use of CBCT was first provided by Horner and co-workers (2009), who developed 20 basic principles for the use of CBCT by using an online survey among members of the European Academy of Dentomaxillofacial Radiology. This was followed by guidelines published by the European SEDENTEXCT project (www.sedentexct.eu) of the European Atomic Energy Community which comprehensively reviewed and discussed reasons for justification of CBCT for a wide range of indications. It was found that determining a proper role of CBCT imaging will require studies to develop evidence-based selection criteria. Recently, the first systematic review emanating from this project has been published (Guerrero et al. 2010). Guerrero and co-workers have evaluated the evidence for diagnostic efficacy of CBCT examinations of impacted teeth. The inclusion criteria for the review were a description of diagnostic accuracy efficacy, diagnostic thinking efficacy, therapeutic efficacy or any combination of the preceding which corresponds to level 2, 3 and 4 of the six-level hierarchical model described by Fryback & Thornbury (1991). Of 96 scientific papers found in the literature search, seven were considered relevant. Only two of the seven studies had a valid reference method and presented the results in terms of percentage of correct diagnoses.

Consequently, Guerrero and co-workers pointed out the need for randomized controlled trials where findings from CBCT examinations are analyzed in relation to treatment outcome.

Today, the most common indications for cone beam imaging are, apart from assessments for placement of dental implants and in endodontic diagnosis, evaluation of the proximity of the lower third molar to the mandibular nerve prior to extraction (Tantanapornkul et al. 2007, 2009), evaluation of teeth and bone for signs of cysts and tumours (Ziegler et al. 2002, Quereshy et al. 2008, White & Pharoah 2008), examination of teeth and facial structures for orthodontic treatment planning (Scarfe & Farman 2008, Hechler 2008) and evaluation of the temporomandibular joint for osseous degenerative changes (Honda et al. 2006, Lewis et al. 2008). Cone beam imaging have largely replaced conventional tomography and to some extent also conventional CT for these tasks. The two most common dental diseases affecting humans are dental caries and periodontal disease. Regarding dental caries Zhang and co-workers (2010) found no evidence for a better diagnostic accuracy with CBCT technique instead of intra-oral radiography even when no dental restorations were present. For periodontal disease the intra-oral radiography, will also be the technique to choose as long as software programmes are not available decreasing artefacts from dental fillings and crowns. Studies concerning accuracy for periodontal disease have mostly been made on dry skulls with teeth without dental restorations (Misch et al. 2006, Noujeim et al. 2009). The radiation dose has also to be taken into consideration and the fact that there is a lack of evidence for better treatment outcome and thus more beneficial to the patient by using the CBCT technique.

To sum up the advantages of the CBCT technique lower radiation dose than for conventional CT, ability to image small volumes on certain systems, high resolution images, availability of 3D and cross-sectional images, accurate measurements and reduced superimposition of overlying bony tissues resulting in improved diagnosis and treatment planning can be mentioned. Among the disadvantages higher radiation dose than for other dental imaging techniques and additional radiation exposure if used in addition to other dental imaging techniques have to be taken into account. Further, the capital cost of the systems and the requirement of additional interpreting and reporting time have to be included among the disadvantages. Compared to conventional CT the limitations are the lack of Hounsfield units, lack of a soft tissue window, and higher image noise.

Further technical improvements of the CBCT systems can be anticipated in the future. Some CBCT manufactures have already introduced artefact reduction algorithms within the reconstruction process (Suomalainen 2010) and another has added filtration to reduce radiation dose (Qu et al. 2010). In addition, anti-scatter grids, scatter reduction algorithms and beam filters will probably be developed in an attempt to minimize the scatter in CBCT. There is a need for CBCT systems, which allow variation of FOVs and resolution making it possible to select task-specific protocols. Furthermore, multi-modal imaging systems including conventional panoramic and cephalometric images in addition to CBCT will most likely be a future trend.

To conclude, CBCT is a valuable imaging method in dentistry because in many important respects CBCT images are superior to other radiographic techniques that it is to replace. Cone beam CT images can readily display accurate measurements, a particularly important feature for implant planning. Further, limited volume CBCT provides images at high spatial resolution, an important feature for periapical diagnosis, and at low radiation doses. Cone beam CT imaging will continue to mature rapidly. In this context the DAP method can fulfill a need for determining diagnostic standard doses and dose reference levels in an easy way. However, if effective dose is requested a general acceptance for what conversion factors to use in dental radiology is needed. Undoubtedly, CBCT will play an increasingly important role in dentistry but studies are needed on patient outcome level and thus ascertain that the technique will be properly used.

Conclusions

From the results of *Studies I-IV* the following conclusions were drawn:

- cone beam CT with a limited volume (3D Accuitomo) is well suited for the diagnosis of periapical pathology in selected cases, as in planning for endodontic surgery in multi-rooted teeth and when clinical findings or subjective symptoms do not agree with findings in intra-oral radiographs.

- a high agreement was found among observers evaluating visibility of marginal bone crest and mandibular canal in cone beam CT images (3D Accuitomo) making the technique suitable for implant planning.

- the CTDI method was found not to be applicable in estimating effective dose for limited volume cone beam CT (3D Accuitomo and 3D Accuitomo FPD).

- dose-area product (DAP) was found to be a useable method for estimation of effective dose for cone beam CT (3D Accuitomo and 3D Accuitomo FPD). However, further studies to find generally accepted conversion factors are needed.

- the effective dose, estimated with the recommendations of ICRP 60 (1991), varied between 11-77 µSv for three selected examinations (implant planning in the posterior mandible and examinations of impacted lower third molars and retained upper cuspids) with cone beam CT (3D Accuitomo and 3D Accuitomo FPD).

- the diagnostic task periapical diagnosis required higher exposure settings regardless of jaw and FOV than did implant planning. For implant planning higher exposure settings were required in the lower jaw, regardless of FOV, compared to in the upper jaw. Thus, it is possible to adapt the exposure settings depending on diagnostic task.

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