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Soili Kallio-Pulkkinen

EFFECT OF DISPLAY TYPE AND ROOM ILLUMINANCE IN VIEWING DIGITAL DENTAL RADIOGRAPHY

DISPLAY PERFORMANCE IN PANORAMIC AND INTRAORAL RADIOGRAPHY

UNIVERSITY OF OULU GRADUATE SCHOOL;
UNIVERSITY OF OULU,
FACULTY OF MEDICINE;
MEDICAL RESEARCH CENTER OULU;
OULU UNIVERSITY HOSPITAL

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EFFECT OF DISPLAY TYPE AND ROOM ILLUMINANCE IN VIEWING DIGITAL DENTAL RADIOGRAPHY

Display performance in panoramic and intraoral radiography

Academic dissertation to be presented with the assent of the Doctoral Training Committee of Health and Biosciences of the University of Oulu for public defence in the Leena Palotie auditorium (101A) of the Faculty of Medicine (Aapistie 5 A), on 27 November 2015, at 12 noon

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Supervised by
Docent Sisko Huumonen
Professor Osmo Tervonen
Professor Miika Nieminen

Reviewed by
Professor Kristina Hellèn-Halme
Professor Sauli Savolainen

Opponent
Professor Riitta Parkkola

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Abstract

Today, digital imaging is widely used in dentistry. In medical radiography, the importance of displays and room illuminance has been shown in many studies, whereas the effect of these factors in the diagnosis of dental radiography is not clear and remains controversial. There is limited knowledge among dentists as to how observer performance is affected by the type of display, level of ambient light or grayscale calibration. The aim of this thesis was to compare observer performance in the detection of both anatomical structures and pathology in panoramic and bitewing radiographs using consumer grade display with γ 2.2- and DICOM-calibration, a tablet (3rd generation Apple iPad® and a 6 MegaPixel (MP) display under different lighting conditions. Furthermore, the thesis aimed at providing recommendations for type of display and acceptable illuminance levels in the room for interpretation of dental radiographs.

Thirty panoramic and bitewing radiographs were randomly evaluated on four displays under bright (510 lx) and dim (16 lx) ambient lighting by two observers. Both anatomical structures and pathology were evaluated because they provided both low- and high-contrast structure. Consensus was considered as reference. Intra- and inter-observer agreement was determined. The proportion of equivalent ratings and weighted kappa were used to assess the reliability. The level of significance was set to $P<0.05$.

DICOM calibration may improve observer performance in the detection of pathology in panoramic radiographs regardless of the room illuminance level. DICOM calibration improves the detection of enamel and dentinal caries in bitewing radiographs, particularly in bright lighting conditions. On the other hand, in dental practice the room illuminance level is often higher, and it is thus recommended that the overall lighting level should be decreased. Furthermore, a DICOM-calibrated consumer grade display can be used instead of a medical display in dental practice without compromising the diagnostic quality and it saves costs. Tablet displays are recommended to use with care in dental radiography.

Keywords: bitewing radiographs, DICOM, display, grayscale calibration, GSDF, illuminance, panoramic radiographs

Kallio-Pulkkinen, Soili, Näyttöjen suorituskyky panoraama- ja intraoraalikuvien tulkinnassa eri valaistusolosuhteissa.
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Tiivistelmä

Hammaslääketieteessä käytetään nykyään pääasiassa digitaalista kuvantamista. Lääketieteellisessä radiologiassa näyttöjen ja käyttöympäristön valaistuksen merkitys kuvien katseluun on osoitettu lukuisissa tutkimuksissa, kun taas hammaslääketieteellisten tutkimusten tulokset näiden tekijöiden vaikutuksista röntgenkuvien tulkintaan eivät ole yksiselitteisiä ja niissä on ristiriitaisuutta. Hammaslääkäreiden tiedot näyttöjen, kalibroinnin ja ympäröivän valaistuksen vaikutuksesta röntgenkuvan tulkintaan ovat puutteellisia. Tämän väitöskirjan tarkoituksena oli vertailla näyttöjen suorituskykyä panoraama- ja purusiivekekuvien tulkinnassa eri valaistusolosuhteissa. Tutkimuksessa vertailtiin γ 2.2- ja DICOM-kalibroitua perusnäyttöä, tablettia (kolmannen polven Apple iPad®) sekä 6 MegaPikselin (MP) lääketieteelliseen käyttöön tarkoitettua näyttöä. Lisäksi väitöskirjan tarkoituksena oli antaa hammaslääketieteellisten röntgenkuvien katseluun soveltuvia näyttöjä ja käyttöympäristön valaistusta koskevia suosituksia.

Kaksi tulkitsijaa arvioi 30 panoraama- ja purusiivekeröntgenkuvaa satunnaisessa järjestyksessä neljältä eri näytöltä kirkkaassa (510 luksia) ja hämärässä (16 luksia) valaistuksessa. Tutkimuksessa arvioitiin sekä korkeakontrastisia anatomisia rakenteita että matalakontrastisia patologisia löydöksiä. Tuloksia verrattiin tutkijoiden väliseen yhteisluentaan. Luotettavuuden arviointiin käytettiin yhdenmukaisuusosuutta sekä painotettua kappaa. Toistettavuuden arvioimiseksi laskettiin kapat toisen alkuperäisten ja uusintaluentojen sekä molempien tulkitsijoiden alkuperäisluentojen välille. Merkitsevyystasoksi määriteltiin $p<0,05$.

DICOM-kalibrointi voi parantaa patologisten löydösten tulkintaa panoraamakuvissa molemmissa valaistusolosuhteissa. DICOM-kalibrointi parantaa selvästi purusiivekekuvien hammaskiille- ja hammasluukarieksen tulkintaa erityisesti kirkkaassa valaistuksessa. Hammaslääkäreiden työskentelytilojen valaistus on yleensä korkeampi kuin tutkimuksessa käytetty, joten näyttöjen käyttöympäristön valaistusta tulisi laskea toimistovalaistusta vastaavaksi. DICOM-kalibroitua perusnäyttöä voidaan suositella käytettäväksi kalliiden medikaalinäyttöjen sijaan. Tablettia tulee sen sijaan käyttää harkiten hammaskuvien tulkintaan.

Asiasanat: DICOM, GSDF, harmaasävykalibrointi, näyttö, panoraamaröntgenkuva, purusiivekeröntgenkuva, ympäröivä valaistus

God`s Riches At Christ`s Expence

With love to Harri, Jukka-Pekka and Joona
To all my family

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Abbreviations

L	Luminance. A photometric measure of the luminous intensity per unit area projected in a given direction. SI unit for luminance is candela per square meter (cd/m^2)
L_{amb}	The combination of light reflection from various surfaces to produce a uniform illumination. Ambient light reduces the contrast in the image
L_{max}	Maximum luminance of a display
L_{min}	Minimum luminance of a display
lx	The SI unit of illuminance (lux)
2D	2-dimensional
3D	3-dimensional
i.e.	id est, that is
e.g.	exempli gratia, for example
AAPM	The American Association of Physicists in Medicine
ACR	The American College of Radiology
BW	Bitewing
CBCT	Cone-Beam Computed Tomography
CCD	Charge-Coupled Device
CCFL	Cold-Cathode Fluorescent Lamp
CMOS	Complementary Metal Oxide Semiconductor
CRT	Cathode Ray Tube
DDL	Digital Driving Level. A digital value which given as input to a display system produces a luminance
DICOM	Digital Imaging and Communication System in Medicine. A standard for handling, storing and transmitting information in medical imaging
FDA	The U.S. Food and Drug Administration
Gamma 2.2.	The parameter that describes the nonlinear relationship between the numerical value of a pixel and its brightness on the display
GSDF	Grayscale Standard Display Function. The mathematically defined mapping of an input JNDindex to luminance values defined in PS 3.14
IPS	In Plane Switching
JND	Just Noticeable Difference. The distance between two luminance levels that the human eye can detect

LED	Light Emitting Diode
LUT	Look-Up-Table
NEMA	National Electrical Manufactures Association
MP	MegaPixels
PPS	Phosphor Plate System
RGB	Red Green Blue. Color model in which red, green, and blue light are added together in various ways to reproduce a broad array of colors.
SIIM	The Society for Imaging Informatics in Medicine
SMPTE	The Society of Motion Picture and Television Engineers
STUK	Säteilyturvakeskus. Radiation and Nuclear Safety Authority, Finland
TFT	Thin-FilmTransistor
TG-18 QC	The test patterns to evaluate the performance of display devices
TN	Twisted Nematic

List of original publications

I Kallio-Pulkkinen S, Haapea M, Liukkonen E, Huumonen S, Tervonen O & Nieminen MT (2014) Comparison of consumer grade, tablet and 6MP-displays: Observer performance in detection of anatomical and pathological structures in panoramic radiographs. Oral Surg Oral Med Oral Pathol Oral Radiol Endod 118(1): 135-141.

II Kallio-Pulkkinen S, Haapea M, Liukkonen E, Huumonen S, Tervonen O & Nieminen MT (2015) Comparison between digital imaging and communication in medicine-calibrated and uncalibrated consumer grade and 6-MP displays under different lighting conditions in panoramic radiography. Dentomaxillofac Radiol 44(5): 20140365.

III Kallio-Pulkkinen S, Huumonen S, Haapea M, Liukkonen E, Sipola A, Tervonen O & Nieminen MT (2016) Effect of display type, DICOM-calibration and room illuminance in bitewing radiographs. Dentomaxillofac Radiol 45: 20150129.

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1 Introduction

Digital radiography has revolutionized radiology. This revolution is the result of technologic innovation in image acquisition, retrieval, transmission and interpretation. Expert consensus from the fields of medical radiology and physics highlight the important relationship between display performance and digital image interpretation. This has important consequences for the practice of digital radiography in dentistry. It is important to ensure that displays do not compromise image quality or patient care (Samei *et al.* 2005a).

In clinical practice, bitewing radiographs are taken to detect and monitor the progression of caries and to assess periodontal status. Panoramic radiography is a common examination covering both jaws and facial structures and it is often used as the initial evaluation image. Radiographs are also an important component in assisting with the appropriate treatment and follow-up of patients (White & Pharoah 2009: 297-313). Digital radiography has been used in dentistry for the past decade. Many factors influence the quality of digital radiographs. This system has been named the 'digital imaging chain' (Carino 2002, Samei 2002, Leachtenauer 2004). Digital radiography requires an X-ray device; in addition, an image receptor, computer and software are needed for the acquisition, processing and storage of image data. The final link in the chain is a display and an environment where radiographs are interpreted.

New technology has brought many benefits but also new problems. For example, with analog film no manipulation of the image is possible after chemical processing has been completed, whereas in the case of digital radiographs, post-processing is possible, offering a possibility to enhance image quality. The final quality of a digital radiograph is dependent on how electronic information is passed on through the whole imaging chain (Krupinski *et al.* 2007). One of the weaker factors in the process appear to be displays (Samei 2003). Another factor that may influence diagnostic outcome is the level of ambient light in the viewing room.

The American Association of Physicists in Medicine (AAPM 2013, Samei *et al.* 2005a) and the American College of Radiology (ACR 2014) have provided national guidelines regarding acceptable illuminance levels in the room used for radiographic interpretation and grayscale calibration. The basic principle is that the displays show grayscale images according to the Digital Imaging and Communication (DICOM) part 14: grayscale standard display function (GSDF) (DICOM PS3.14 2015). This relationship ensures that differences in grayscale are shown optimally to the human eye (Barten 1999). The GSDF curve has been derived from Barten's experiments with human observers determining their contrast thresholds over the complete grayscale range. The purpose of the grayscale calibration is to ensure the optimal presentation and perception of contrast in digital radiography, and to ensure that an image is presented "identically" over time and different locations. This standard is in use in medical displays, such as 6MP displays. These displays are expensive; and the reason why medical displays are not replaced with consumer grade displays without calibration is probably due to lack of knowledge of how the calibration affects the diagnostic accuracy of digital radiographs. In addition, the radiographs are often interpreted using the same display that is used for maintaining patient records. Furthermore, a significantly higher room illuminance (1000 lx) is recommended for clinical work in dental practices (Swedish Standard Institute 2011). All in all, there is limited knowledge among dentists of how observer performance is affected by the type of display, level of ambient light or grayscale calibration (Hellèn-Halme *et al.* 2007, Odlum *et al.* 2012).

Several systems are currently available for viewing digital images, mostly high-resolution calibrated grayscale displays, consumer grade color displays and, most recently, tablets. Several *in vitro* studies have investigated the effect of varying displays on detecting interproximal caries in digital intraoral radiographs (Shintaku *et al.* 2012, Hellèn-Halme *et al.* 2008, Hellèn-Halme *et al.* 2009, Hellèn-Halme *et al.* 2012, Hellèn-Halme *et al.* 2013). In these studies some technical parameters were investigated, i.e., the effect of DICOM calibration, ambient light, luminance and monitor contrast and brightness settings. Hellèn-Halme *et al.* concluded that the diagnostic accuracy of dentinal carious lesions was significantly higher in ambient light of less than 50 lx (Hellèn-Halme *et al.* 2008). Odlum *et al.* reported that the use of the DICOM GSDF significantly improved the diagnostic accuracy in endodontic and periodontal diagnostics of intraoral radiographs (Odlum *et al.* 2011). Otherwise, in these and a few other studies, the authors have reported that overall accuracy of caries detection in intraoral images is not affected by display type, i.e., consumer grade, tablet or medical display (Ludlow 1999, Cederberg 1999, Isidor 2009). So far, two clinical studies have reported the effect of different displays on bitewing radiographs (Shintaku *et al.* 2012, Araki *et al.* 2015). Only three studies have evaluated the effect of display type on panoramic radiographs (Kim *et al.* 2011, McIlgorm *et al.* 2013, McIlgorm & McNulty 2015). Apart from these studies, the effect of ambient light level and display type on observer performance in panoramic radiographs has not been investigated.

The purpose of this thesis was to compare observer performance in the detection of anatomical structures and pathology in panoramic and bitewing radiographs using different displays in bright and dim lighting conditions, and provide recommendations for type of display and acceptable illuminance levels in the room for the interpretation of dental radiographs.

2 Review of the literature and technology

2.1 Digital radiography

Digital radiography has several advantages compared to analog radiography. Instead of analog devices, digital radiography uses a digital image capture device. This gives the advantages of immediate image preview and availability, a wider dynamic range, which makes it more forgiving for over- and under-exposure. Film and dark-room processing are avoided, and the images can be digitally transferred and enhanced. The absorbed dose to the patient can be lowered with the digital technique (Berkhout *et al.* 2004). The aim of the radiography system should be to display radiographs of optimal quality. Many factors influence the quality of digital radiographs, such as obtaining the raw data, data processing, image display and interpretation of the image by the observer. This system has been named the 'digital imaging chain' (Carino 2002, Samei 2002, Leachtenauer 2004). In addition to an X-ray device digital radiography requires an image receptor, computer and software for image data acquisition, processing and storage. The final link in the chain is a display and an environment where radiographs are interpreted (Sorantin 2008).

2.2 Diagnosis in dental radiography

The decision to perform a radiographic examination should be based on the individual needs of the patient. These needs are defined by findings from the clinical examination and the dental history modified by the patient's general health and age. Radiographic exposures are justified when the clinical examination and history have not provided enough information to enable evaluation of the patient's condition and to make an appropriate treatment plan. Furthermore, they should only be undertaken when it is more likely that the patient will benefit from the discovery of valuable information from the radiograph and it will contribute to patient care. Dental radiographs are taken to detect disease, to monitor the progression of known diseases and in follow-up of patients. Screening of patients is not acceptable in dental care.

Many kinds of lesion occur in the maxillofacial regions. Some types of lesions such as fractures or tumors occur in other parts of the body as well. However, there are some lesions that only occur in the jaws. Dentinal carious and periapical lesions are good examples of such lesions. Accurate radiographic diagnosis is an important task for the dentist in assisting with the appropriate treatment and follow-up of patients (White & Pharoah 2009: 297-313). Panoramic radiographs are taken on initial examination covering the maxillofacial regions, and bitewing radiographs are taken to detect and monitor the progression of caries and to assess periodontal status (Figures 1 and 2). In 2011, approximately 3.9 million X-ray examinations were made in Finland. This number included 2.3 million intraoral radiographs and 400,000 panoramic radiographs taken of a population of about 5.4 million (Helasvuo 2013).

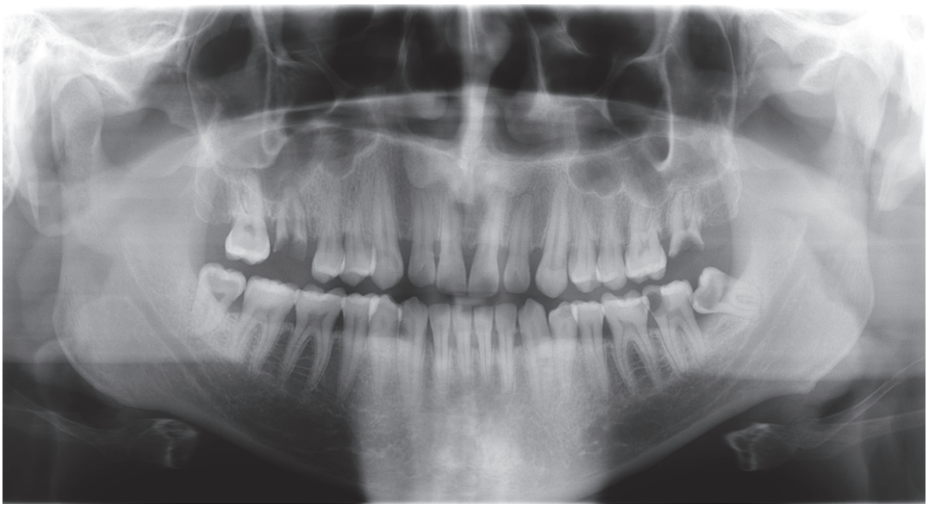

Fig. 1. Example of panoramic radiograph.

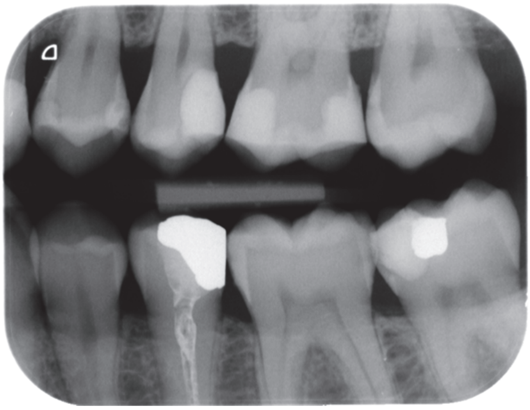

Fig. 2. Example of bitewing radiograph.

Dental caries is one of the most prevalent chronic inflammatory diseases worldwide (Selwitz & Ismail 2007). Caries causes demineralization of the dental hard tissues. With caries progression, demineralization may progress through the enamel and the dentin, and finally into the pulp. The state of disease is usually diagnosed clinically by classification of carious lesions by a visual examination (Pitts 2004, Ismail *et al.* 2007, Topping & Pitts 2009). In clinical access to interproximal carious lesions may be limited, particularly in the molar regions. It has been estimated that only ~12–50% of interproximal carious lesions are determined by a visual examination by an experienced dentist (Hintze *et al.* 1998). Radiography is the most commonly recommended adjunct method available in the diagnosis in the interproximal caries (Braga *et al.* 2010). An additional diagnostic value of radiography compared with a clinical examination has been observed in several studies (Pitts & Kidd 1992, Pooterman *et al.* 1999, Machiulskiene *et al.* 2004, Lillehagen *et al.* 2007, Mialhe *et al.* 2009). Pitts (1996) reported that bitewing radiograph detects more than 90% of the total number of diagnosed interproximal lesions (Pitts 1996). The bitewing radiograph is therefore the most commonly used radiograph for detecting caries (Figure 2).

Demineralization is seen in the radiographs as a radiolucent zone due to the demineralized area of the enamel and/or the fact that dentin does not absorb as many X-ray photons as the unaffected tooth. The classical shape of the early radiolucent lesion in the enamel is a triangle with its top point to the dentin, but other appearances are common as well, such as a dot, a notch, a band or thin lines (Wenzel 2009). Interproximal carious lesions most commonly develop between the contacting proximal surfaces of two adjacent teeth. Because the proximal surfaces of molars are often large, small amounts of mineral loss are often difficult to detect in the radiograph (Eli *et al.* 1996, Weiss *et al.* 1996). Approximately 30% to 40% demineralization has to have occurred until the lesions in enamel can be detected (Wenzel 2009). Dental anomalies such as hypoplastic pits and concavities can mimic the appearance of caries, presenting a false-positive finding. On the contrary, in cases where radiolucency is not yet seen in the radiograph, failure to detect the lesions is a false-negative finding. A lesion penetrating into the dentin in the radiograph may be easier to detect. Studies have reported that lesion depth can be fairly accurately estimated on radiographs when compared to the depth of the caries lesion histologically (Jacobsen *et al.* 2004, Young & Featherstone 2005). Furthermore, these lesions are equally 'under-scored' as 'over-scored' when compared to lesion depth in histological sections of the tooth (Jacobsen *et al.* 2004). The lesions detected in the enamel need to be restored with conservative intervention whereas lesions penetrating into dentin usually need operative treatment. In the cases where a decision is taken to monitor the lesion, timing of a follow-up radiograph should be determined individually. (de Vries *et al.* 1990, Bader & Shugars 1997, Wenzel 2009).

One of the most important clinical issues that general dentists are faced with are periapical inflammatory lesions. A periapical inflammatory lesion is defined as local response of the bone around the apex of the tooth that occurs secondary to necrosis of the pulp or through surrounding tissues by periodontal disease. The necrosis may occur secondary to deep caries lesions or trauma. The periapical inflammatory lesions, apical periodontitis, may histolocigally represent either a periapical granuloma or abscess. The diagnosis of apical periodontitis is essential to determine the selection of effective dental treatment including root canal treatment, resection or even extraction. The radiographic features of apical periodontitis vary depending on the time course of the lesions from very early periapical inflammatory lesions, i.e., widening of the periapical periodontal ligament space at the apex of the tooth twice from normal (0.5 – 0.8 mm) to osteomyelitis. (Lee 2009).

The radiograph corresponds to a 2-dimensional view of a 3-dimensional structure (Bender & Seltzer 1961). Artificial periapical lesions produced in cadavers have revealed that these lesions can be detected by conventional radiographs only if perforation, large destruction of the bone cortex on the outer surface, or erosion of the cortical bone is present (Estrela *et al.* 2008). Furthermore, lesions with buccal or lingual cortical involvement with 30% to

50% of bone mineral loss can be detected in radiographs (Bender & Seltzer 1961). The locations of lesions in different types of bone also affect the radiograph visualization (Huumonen & Ørstravik 2002).

2.2.1 Panoramic radiography

Panoramic radiography is one of the most widely used radiological diagnostic techniques in dental practice, offering full vision of the jaws and adjacent regions, and it is often used as the initial examination (Figure 1). Interpreting normal anatomical structures on panoramic radiographs is challenging because of the complex anatomy of the midface, the superimposition of various anatomic structures and the many potential artifacts associated with receptor and x-ray source and patient movement and patient positioning (White & Pharoah 2009: 200–209). If patient positioning and head alignment are done correctly, and there are no exposure errors, anatomical structures, such as the border of the maxillary sinus, and pathology, such as dentinal caries and periapical lesions, should be seen.

The borders of the maxillary sinus should be outlined with intact cortical bone. If the cortical bone is destroyed it could be a sign of inflammatory odontogenic disease or even malignancy. Very early periapical inflammatory lesions, i.e., widening of the periapical periodontal ligament space at the apex of the tooth twice from normal in the upper permanent molars, are difficult to detect against the air-filled maxillary sinus (Kim *et al.* 2011, White & Pharoah 2009: 200–209). Inflammatory changes in the sinuses, such as thickened mucous membrane and periosteal reaction in the adjacent floor of the maxillary sinus, may be caused by chronic periapical infection. This kind of pathology must be interpreted on panoramic radiographs and assessed for the need for further investigation, i.e., intraoral imaging or even 3D examination. Periapical and pathological lesions are difficult to detect on 2D radiographs (Odlum *et al.* 2012, White & Pharoah 2009:200–209).

Previously, it had been concluded that subjective image quality between conventional panoramic images and digital panoramic radiographs was comparable in both anatomical and pathological findings, e.g. caries and periapical lesions (Baksi *et al.* 2010, Mahesh *et al.* 2011, Peker *et al.* 2009).

2.2.2 Intraoral radiography

Intraoral radiography is the most common radiographic examination in general dental practice (Helasvuo 2013). Intraoral radiographs can be divided into three categories: periapical, bitewing, and occlusal radiographs. In periapical radiographs all of the teeth and at least 2 mm of the periapical bone should be seen. Occlusal radiographs show a larger area of the teeth and bone than periapical radiographs. Bitewing radiographs show both upper and lower crowns and the maxillary and mandibular alveolar crests. Furthermore, the bitewing technique is most commonly used for detecting carious lesions and the most commonly used radiographic projection among general dental practitioners (Wenzel 2006). To avoid the distortion of radiographs, overlapping, and to get the same image geometry in follow-up radiographs of the same teeth, standardized receptor holders with a beam-aiming device should be used with periapical and bitewing techniques (Pitts *et al.* 1991, Pierro *et al.* 2008).

An increasing number of general dental practitioners have substituted analog film with digital radiography. The digital receptor may be a charge-coupled device/complementary metal oxide semiconductor (CCD/CMOS) sensor system with or without a cord that connects the receptor to the computer or phosphor plate sensor (PPS) which is processed in a scanner after exposure (Wenzel & Møystad 2010). Several studies have compared film and digital radiography, concluding that no significant differences exist between these modalities (Abreu jr M *et al.* 2001, Berkhout WR 2007, Erten H *et al.* 2005, Hinze & Wenzel 2002, Hintze *et al.* 2002, Khan *et al.* 2005, Kullendorf *et al.* 1997, Nair MK & Nair UP 2001, Syriopoulus *et al.* 2000, Svanæs *et al.* 2000,Uprichard *et al.* 2000, Wenzel 1998, Wenzel 2000, Wenzel 2004).

2.3 Type of display

In principle, classification of display type describes the technology applied by the display to produce light. Displays present radiographs throughout the process, beginning with the collection of information gathered during image acquisition. This information undergoes conversion by the graphics card into electronic signals which control the amount of light generated by the display for radiograph production (Sorantin 2008).

Today, liquid crystal displays (LCD) have replaced cathode ray tube displays (CRT) in radiography. On the back of the LCD there is a fluorescent light source:

a Cold-Cathode Fluorescent Lamp, CCFL or Light-Emitting Diode, LED. CCF lamps can also placed at opposite edges of the display. Light is sent through modulating light transmission windows, liquid crystal cells, of a flat-panel display.

Today, displays have started to use an active-matrix structure. A matrix of thin-film transistors (TFTs) is added to the electrodes in contact with the liquid crystal layer. The application of an electrical field through this transistor affects the orientation of the liquid crystals in each pixel (liquid crystal cell) between polarizing filters. Each pixel has its own dedicated transistor. The orientation of these crystals controls the orientation of the polarizing filters and the transmission of light. LCD displays contain liquid crystals that twist and untwist at varying degrees to allow light to pass through. When no voltage is applied to a twisted nematic liquid crystal cell, polarized light passes through the 90-degree twisted liquid crystal layer. In proportion to the voltage applied, the liquid crystals untwist, changing the polarization and blocking the light's path. By properly adjusting the level of the voltage almost any gray level or transmission can be achieved. The structure of an LCD display is shown in Figure 3. Twisted Nematic (TN) pixel structure depends on the viewing angle, degrading image brightness, contrast, and color. (Badano 2003, Fetterly *et al.* 2008). According to ACR-AAPM-SIIM (2013), instead of TN displays IPS (In Plane Switching) pixel structure which provides improved viewing angle performance should be used. In the IPS liquid crystal cells remain parallel to the front and back panels rather than turning perpendicular when a voltage is applied.

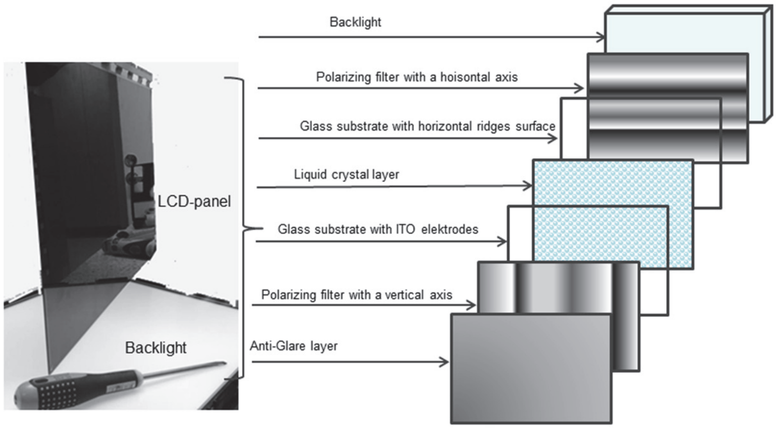

Fig. 3. Liquid crystal display structure. The image of panel and backlight (left) and the schematic drawing in these structures (right) (modified from Sorantin 2008).

In a color display each pixel is divided into three sub-pixels: red, green and blue, so-called "RGB" sub-pixels. The color of a pixel can be changed to change the brightness of each sub-pixel on both color and monochrome displays.

Displays are also classified according to the purpose for which they are used. Displays for medical radiography are classified as either primary or secondary grade displays. Primary displays are used for the interpretation of medical radiographs upon which a diagnosis is made. These displays comply with the highest standards (Samei *et al.* 2005, STUK 2008). Secondary displays are used to view radiographs for another purpose than providing a medical diagnosis (e.g., used by clinicians or technicians).

2.4 Display performance standards in diagnostic medical radiology

Several organizations have provided standards for displays used in diagnostic radiology. The primary purpose of these guidelines is to ensure that displays perform uniformly and consistently and to demonstrate the degradation of image quality on suboptimal displays (Jervis & Brettle 2003, Badano 2004, Wade & Brennan 2004, Samei *et al.* 2007, Hellèn-Halme *et al.* 2007, Krupinski *et al.* 2007). These guidelines have been drawn up based on expert consensus (AAPM 2013).

The Society of Motion Picture and Television Engineers (SMPTE) Recommended Practice 133-1991, 'SMPTE 133-1991' was one of the first guidelines to refer to the assessment of medical display quality (SMPTE 1991). Recently, the American Association of Physicist in Medicine (AAPM), the National Electrical Manufactures Association (NEMA), and the American College of Radiology (ACR 2014) have developed new guidelines: the Assessment of Display Performance for Medical Imaging systems (AAPM Task Group 18) (AAPM 2013) and the Digital Imaging and Communications in Medicine (DICOM) Part 14 Grayscale Standard Display Function standard (Nema 2015), DICOM PS3.14. These standards provide guidance and tools for the acceptance and quality testing of medical displays.

The fast growth of digital imaging in healthcare and recognition of the importance of displays has prompted the development of these standards (Ly 2002, Jervis & Brettle 2003, Crespi *et al.* 2006a, Crespi *et al.* 2006b).

2.5 Factors impacting display performance

Graphics cards

Graphics cards convert an electronic signal into a digital driving level (DDL) which is then used to developed an image. Low-quality graphics cards are physically unable to support and present appropriate amounts of data and degrade the quality of the image (Wang *et al.* 2003, Badano 2004). Low-quality graphics cards are often included in consumer grade displays. Whereas high-quality graphics cards are able to re-scale pixels according to AAPM TG18 and DICOM PS3.14 standards. These cards are recommended and often included in medical displays.

Luminance and contrast

Luminance refers to the amount of light emitted from the display surface. It consists of a light produced by the display that varies between minimum luminance (L'min) to maximum luminance (L'max), affected by diffusely reflected ambient light (Lamb). The unit is candela per meter squared (cd/m^2). According to the American College of Radiology a display should have a luminance of at least 350 cd/m^2 (ACR 2014).

Different levels of luminance are comprehended as contrast. The term contrast ratio refers to the differences between maximum and minimum luminance (L'max/L'min) measured at low ambient lighting. The contrast ratio is referred to as the dynamic range of the display: it refers to the number of shades of gray. This value is used to characterize a display: e.g. in grayscale displays the value of the contrast ratio is about 600 and in color displays 250 - 400 (Fetterly *et al.* 2008). 'Luminance ratio' refers to L'max/L'min in the presence of an ambient light considered as a display function. (Samei *et al.* 2004).

Contrast response is the term used to describe the capability of a display to reliably and accurate present grayscale in response to an input signal (AAPM TG18) 2013). AAPM TG18 and NEMA have developed standards for the contrast response of a display (AAPM 2013, NEMA 2015). In medical displays these standards come true. Many consumer grade displays have large contrast ratios; however, it is still important to bear in mind that the presentation of grayscale in that range is inconsistent because they do not conform to DICOM PS3.14 standards. Therefore, medical displays will present grayscale values with major accuracy in comparison with consumer grade displays that have not been manufactured or calibrated according to these standards.

Luminance uniformity

Luminance uniformity defines the emission of light across the surface of a display (AAPM 2013). Significant variation in this emission across the display area affects the contrast of displayed images. In LCD displays, non-uniformity is often caused by uniformity of the backlight, uniformity of the liquid crystal layer (variations in its thickness), and uniformity of the quality of the pixel architecture. Uniformity of the backlight is usually caused by degeneration due to ageing.

Illuminance

Illuminance is a photometric term to use to describe the amount of ambient light or the light striking a display surface. The unit is lux (lx). High illuminance degrades contrast and image quality (Samei *et al.* 2004, Fetterly *et al.*2008, AAPM 2013). Table 1 shows illumination of display surface in various healthcare facilities. Illuminance is lowest in hospitals where there are diagnostic reading facilities and highest in clinical dental practices.

Table 1. Typical illuminance levels (modified from Semei *et al.* 2005b).

Workplace	Illuminance (lux)
Dental clinical practices	1000
Operating rooms	300-400
Emergency medicine	150-300
Hopsital clinical viewing deparments	200-250
Staff offices	50-180
Diagnostic reading departments (CT, MRI, NM)	15-60
Diagnostic reading department (X-ray)	2-10

The reflection of displays consists of both specular and diffuse reflection. In specular reflection, the light is reflected back to the observer from the display surface with minimal angular spread, as from a mirror, which is a smooth surface. Diffuse reflection describes reflection off rough surfaces such as light-colored clothing and paper, reflected diffusely from the display surface (AAPM 2013). Immoderate display reflection interferes with the detection of image contrast by the observer (Wade C & Brennan 2004, Wang & Langer 1997), which is why reflections from ambient light sources, such as lighting in the reading area, should kept at a minimum. According to Krupinski *et al.* (2007), about 25 to 40 lx is generally sufficient to avoid most reflections, yet providing sufficient light for the human visual system to adapt to the displays and surrounding environment (Krupinski *et al.* 2007). Furthermore, indirect and backlight incandescent lights with dimmer switches are recommended.

Resolution

Resolution is the quantitative measure of the capacity for distinguishing fine details in the image (Samei 2005c). Display resolution commonly refers to the number of distinct pixels in each dimension that can be displayed and it is simply the physical number of columns and rows of pixels creating the display (e.g. 2048 × 1536), the so-called matrix provided by the video graphics controller. Display resolution is affected by a pixel's size, referred to as pixels per inch and pixel pitch (the physical spacing between the pixels: 0.200 mm and not larger than 0.210 mm), and the consistency of the display to accurately present contrast (luminance response) (Badano 2004, Andriole 2005). Pixels are the smallest picture element of the display through which light is displayed. Images viewed on displays with smaller, more closely spaced pixel elements seem to be sharper with better resolution than on displays with larger and more widely spread elements (Samei 2005c). Larger and more widely spread pixel elements are usually associated with low-grade displays; conversely, high-quality medical displays have smaller and closely spaced pixel elements (Badano 2004). Displays should offer images with sufficient pixel density to allow displaying the whole image with adequate spatial detail at a viewing distance of 30 to 60 cm. The matrix size of the display should be as close to the pro-processing image data as possible, or obtainable with magnification. Furthermore, if the display matrix size differs from the detector element matrix, for those images zooming display functions are required, so that the resolution of display does not limit the resolution of the displayed image (Krupinski *et al.* 2007). There seems to be consensus that for chest radiography or mammography, the screen size should be at least 54 cm (21 inches) with (5MegaPixels) 2048 × 2560 pixels and spatial resolution (i.e., the capacity for distinguishing fine detail) > 2.5 lp/mm (Sorantin 2008). Detectors of panoramic devices can provide relatively large matrix areas (2976 × 1536) with pixels less than 100 μm and spatial resolution 5.5 lp/mm. Currently the highest resolution detectors in dentistry have pixel size 20 μm, and a theoretical resolution of 25 lp/mm can be obtained. The theoretical resolution limit is determined by pixel size: the smaller the size of the pixel, the higher the maximally achievable resolution. (White & Pharoah 2009: 231-232). Presenting image data on a display with inadequate resolution will jeopardize the accuracy of the radiological interpretation (Cha *et al.* 2009).

Bit depth

The bit depth specifies the maximum number of gray levels. Each bit is binary, 0 or 1, so the total number of gray levels is the bit depth raised to the power of two (for example 8 bits = 2^8 = 256 gray levels). Different imaging devices in radiology can produce images from 12 to 16 bits (2^{12}–2^{16} as 4096–65536 gray levels), whereas LCD displays can attempt 8–12 bits (2^8–2^{12} 256–4096 gray levels). The bit depth of a display is usually determined by the graphics card used in the display. According to ACR-AAPM-SIIM (2014), no evidence has been found to date that diagnostic interpretations are affected by the use of higher than 8-bit systems (ACR-AAPM-SIIM 2014).

Display noise

Display noise means unwanted signals that interfere with true image information (Samei 2005a). Noise should be taken into account because it affects image quality by changing contrast in the image. Noise is affected by many factors such as the number of discrete x-ray photons reaching the detector. In displays, noise contributes to the uniformity of pixel architecture or the uniformity of the liquid crystal layer (AAPM 2013).

Display calibration

Consumer grade displays are gamma-calibrated. Gamma is the parameter that describes the nonlinear relationship between the numerical value of a pixel and its brightness on the display (Figure 4). The purpose of the grayscale calibration is to ensure the consistent presentation of grayscale in the image across a wide range of displays without variation or degradation and to make sure that the presentation of grayscale by displays is correlated to the contrast sensitivity of the human visual system. The American College of Radiology (ACR) and the National Electrical Manufactures Association (NEMA) have provided national guidelines for digital imaging presentation, known as DICOM (Digital Imaging and Communications in Medicine) standards (NEMA 2004, ACR 2014). The basic principle is that displays show grayscale images according to the Digital Imaging and Communication (DICOM) part 14: grayscale standard display function (GSDF) (DICOM PS3.14 2015) (Figure 4). This relationship ensures that differences in grayscale are shown optimally to the human eye (Barten 1999). The GSDF curve has been derived from Barten's experiments with human observers determining their contrast thresholds over the complete grayscale range. The distance between two luminances (i.e., that could just about be defined by the human eye, called just noticeable difference (JND). (Barten 1999). For the luminance range 0.05–4000 cd/m^2, there are 0 to 1023 JNDs as defined by the DICOM PS3.14 (NEMA 2004).

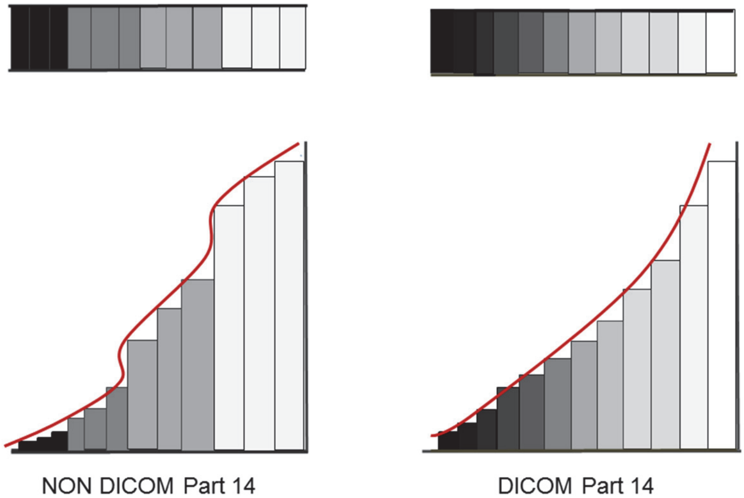

Fig. 4. Effect of grayscale calibration. After DICOM Part 14 calibration the display shows grayscale optimally to the human eye (right), unlike before DICOM Part 14 calibration (left).

2.6 Displays in dentistry

The use of digital radiography has become widespread in dentistry in the past decade. One key area highlighted in literature as having interpretation concerns is the effect of display. In medical radiology, many studies have investigated the performance of display in fields such as chest radiography and mammography etc. (Goo *et al.* 2004, Balassy *et al.* 2005, Liang *et al.* 2006, Buls *et al.* 2007, Fukushima *et al.* 2007, Yamada *et al.* 2008, Kamitani *et al.* 2007), partially in response to ACR and NEMA DICOM PS3.14: GSDF standard (ACR 2014, NEMA 2004). Many medical displays meet this standard, usually automatically, while limited guidelines exist in dental radiology. Among dentists, digital radiography still lags many years behind medical radiography in terms of displays. Furthermore, within the last decade, research in the fields of medical radiology and physics has demonstrated that suboptimally performing displays degrade image quality (AAPM 2013).

2.6.1 Observer performance in panoramic radiographs

Only few studies have investigated the effect of display type in panoramic radiographs. Kim *et al.* (2011) evaluated the effect of liquid crystal display (LCD) display type and observer experience on diagnostic performance of maxillary sinus inflammatory lesions on panoramic radiographs (Kim *et al.* 2011). They compared a high-resolution monochrome LCD (1536×2048, 10 bits, 600 cd/m²) and general color LCD (1240×1024, 8 bits, 200 cd/m²) displays. The ambient light was lowered as much as possible. The study concluded that a less-experienced observer showed lower diagnostic ability with a general color LCD to detect inflammatory changes, such as thickened mucosa on maxillary sinus floor in dark room conditions, compared to an oral radiologist with more than 15 years of experience.

McIlgorm *et al.* (2013) investigated whether calibrating a consumer grade display according to the DICOM PS3.14 would affect the presentation of dental radiographs, and whether there are any differences in the presented radiograph quality between a DICOM-calibrated consumer grade and medical display when displaying 8-bit radiographs including both intraoral and panoramic radiographs (McIlgorm *et al.* 2013, McIlgorm & McNulty 2015). They concluded that calibrating consumer grade display devices to comply with the DICOM PS3.14 can improve the presentation of dental radiographs. They also concluded that a DICOM-calibrated consumer grade monitor is capable of displaying an image quality that is equally preferred to a DICOM-calibrated medical grade monitor for 8-bit dental radiographs. In these studies the ambient light level was set between 25 lx and 40 lx. At the time of publication of this thesis, the use of tablets as devices to view panoramic radiographs had not been investigated.

2.6.2 Observer performance in intraoral radiographs

Studies focusing on the display performance in intraoral radiographs have usually compared the effects of displays and ambient light conditions on the diagnosis of artificial dental caries. Only a few of studies have investigated the effect of display type on diagnosis of other lesions than dental caries, i.e., endodontic treatment and root fracture and impacted tooth diagnostic in intraoral radiographs (Baksi *et al.* 2009, Odlum *et al.* 2012, McIlgorym *et al.* 2013, Tofangchiha *et al.* 2013, McIlgorym 2015). Furthermore, one clinical study has reported the effect of varying displays under bright light conditions in bitewing radiographs (Shintaku *et al.* 2012).

Cederberg *et al.* (1999) compared three medical grade Cathode Ray Tube displays and a laptop in detection of interproximal caries (Cederberg *et al.* 1999). The authors did not detect significant differences in diagnostic accuracy or luminance values, display size, resolution or bit depth. Odlum *et al.* (2012) reported that the use of the DICOM GSDF significantly improved the diagnostic accuracy in endodontic and periodontal diagnostics of intraoral radiographs under 20 to 40 lx. (Odlum *et al.* 2012). No differences were observed between film, CRT and LCD laptop displays in caries detection when the ambient light was not reduced (Ludlow & Abreu 1999).

Hellèn-Halme *et al.* (2009) compared the diagnostic accuracy in caries detection between one consumer grade display with brightness and contrast manually adjusted, and DICOM PS3.14 precalibrated color and monochrome medical LCD displays (Hellèn-Halme *et al.* 2009). They detected no difference between the displays. Similarly, Isidor *et al.* (2009) found no clear relationship between two consumer grade and three medical LCD displays (Isildor *et al.* 2009). In contrast, Ilguy *et al.* (2013) found differences between consumer and medical LCD displays (Ilguy *et al.* 2009). They compared a consumer grade display (800:1, 1280 × 1024, 300 cd/m2) and medical display (900:1, 2048 × 1536, 410 cd/m2) using a storage phosphor plate system. They found that the accuracy of the medical display was significantly higher than that of the consumer grade display in detecting artificial caries. Pakkala *et al.* (2012) compared a consumer grade color display, a DICOM-calibrated color liquid crystal display, and a DICOM-calibrated grayscale liquid crystal display (Pakkala *et al.* 2012). They showed that different displays did not affect the overall detection of caries lesions in intraoral images. Shintaku *et al.* (2012) compared 2nd generation iPad®Apple and consumer grade LCD display in the evaluation of interproximal caries under bright light conditions (Shintaku *et al.* 2012). They concluded that Apple iPad 2® can effectively display radiographs for evaluation, comparably to the LCD display. Furthermore, Shintaku *et al.* concluded that image size did not affect the ability to identify dental caries on the 9.7-inch iPad 2 compared to a 24-inch LCD display, whereas Araki *et al.* (2015) found that the 9.7 inch Apple iPad Air® tablet showed lower diagnostic accuracy than an DICOM-calibrated or consumer grade display, especially for enamel caries in premolars (Araki *et al.* 2015).

Some researchers have also studied the effect of ambient light on diagnostic accuracy in digital radiography. Some studies have reported that ambient light conditions play a significant role in affecting the interpretation of digital radiographs (Arnold 1987, Patel *et al.* 2000, Haak *et al.* 2002). Kutcher *et al.* (2006) showed that the diagnostic accuracy was significantly higher when using hooded laptops compared to bright conditions (Kutcher *et al.* 2006). Also Hellèn-Halme & Lith (2012) found that it was easier to detect dental caries in dim ambient light <50 lx than on consumer grade LCD displays with or without a hood in bright ambient light >1000 lx (Hellèn-Halme & Lith, 2012). When comparing enamel caries, there was no difference between dim and bright ambient light (Hellèn-Halme & Lith 2012). Pakkala *et al.* (2012) compared bright with dim lighting conditions using consumer grade and medical displays (Pakkala *et al.* 2012). In their report, the observers achieved higher sensitivities with lower illuminance settings than with higher illuminance settings. However, this was accompanied by a reduction in specificity, which meant that there was no significant difference in overall accuracy in detection of enamel caries lesions in intraoral radiographs. In addition, Hellén-Halme & Lith (2013) found that there was no difference between dim conditions and bright conditions when the display was calibrated to DICOM PS3.14 standards (Hellén-Halme & Lith 2013).

There are a few studies evaluating the effect of type of display on lesions other than dental caries (Baksi *et al.* 2009, Odlum *et al.* 2012, McIlgorym *et al.* 2013, Tofangchiha *et al.* 2013, McIlgorym 2015). There were no differences between CRT and LCD displays in detection of root canal fillings (Baksi *et al.* 2009). Tofangchiha *et al.* (2013) also concluded that the type of display does not influence diagnosis of vertical root fractures (Tofangchiha *et al.* 2013). On the other hand, Odlum *et al.* (2012) concluded that compared to a consumer grade display, the use of the DICOM Grayscale Standard Display Function significantly improved the diagnostic accuracy in endodontic and periodontal diagnostics of intraoral radiographs (Odlum *et al.* 2012). McIlgorm *et al.* (2013) investigated whether standardizing consumer grade display according to the DICOM PS3.14 would affect the presentation of dental radiographs, and whether there is any difference in the quality of radiographs between a consumer grade and medical display when displaying 8-bit radiographs including both intraoral and panoramic radiographs (McIlgorm *et al.* 2013, McIlgorm & McNulty 2015). They concluded that standardizing consumer grade display devices to the DICOM PS3.14 can improve the presentation of dental radiographs. They also concluded that a DICOM-calibrated consumer grade monitor is capable of displaying an image quality that is equally preferred to a DICOM-calibrated medical grade display for 8-bit dental radiographs. In these studies the ambient light level was set between 25 lx and 40 lx.

3 Purpose of the thesis

The purpose of this thesis was to evaluate the effect of display type, grayscale calibration and room illuminance on panoramic and bitewing radiographs, and to provide recommendations for type of display and acceptable illuminance levels in the room for dental radiographs interpretation. The particular aims were to

1. To compare consumer grade, tablet and 6MP displays: Observer performance in detection of anatomical and pathological structures in panoramic radiographs (I).
2. To compare DICOM-calibrated and uncalibrated consumer grade, tablet and 6MP displays under different lighting conditions in panoramic radiography (II).
3. To evaluate the effect of display type, DICOM-calibration and room illuminance on bitewing radiographs (III).
4. To provide recommendations for type of display and acceptable illuminance levels in the room for interpretation of dental radiographs.

4 Materials and methods

4.1 Study material

The material in Studies I and II consisted of 30 panoramic radiographs that were selected from the patient archive of the Department of Diagnostic Radiology, Oulu University Hospital. The selection criterion for the thirty radiographs was that the structures to be evaluated had to be clearly visible. All images were subjected to routine quality standards, and exposure and/or position errors (e.g. incorrect head position in the image layer) or movement artefacts were not allowed (White SC & Pharoah MJ 2009: 297-313).

The material in Study III consisted of 30 horizontal molar bitewing radiographs that were selected by standard criteria. All images were subjected to routine quality standards, e.g. limited overlap of the approximal surfaces of the teeth was allowed, and both upper and lower crowns and the maxillary and mandibular alveolar crests should be seen. Images taken during a three-month period were selected retrospectively by an oral and maxillofacial radiologist who did not participate in the evaluation.

The selection of radiographs was made using a 6 MegaPixel (6MP) display (Table 2). Ambient light level was 16 lx. Ambient light was measured from the surface of the display in the direction of the viewer using a luminance meter (Unfors RaySafe Xi; Billdal; Sweden).

All radiographs were taken by experienced radiographers. A panoramic device (Instrumentarium Corp., model OP200 D, Tuusula, Finland) was used with exposure settings of 66 kV and 9.9 mA. The bitewings were taken with a storage phosphor plate system (DürrDental AG, Bietingheim-Bissingen, Germany) on a Focus™ Intraoral X-ray unit (Instrumentarium Dental, PaloDex Group OY, Tuusula, Finland) with exposure settings of 70 kV, 7 mA and 0.32 s. The KerrHawe Kwik-Bite® holder (KerrHawe SA, Bioggio, Switzerland) was used. The central beam of the X-ray was positioned to pass at right angles to the long axis of the tooth, and tangentially through the contact area. The plates were read by the VistaScan Mini Plus image plate scanner (DürrDental AG, Bietingheim-Bissingen, Germany). All images were stored as Digital Imaging and Communications in Medicine (DICOM) format file. The Image matrix size was 2976 × 1536 (0.07 × 0.07. mm pixel size at detector) in panoramic radiographs and 1932 × 1496 pixels (0.02 × 0.02. mm pixel size at detector) in bitewing radiographs. The acquired digital raw data were sent to the Picture Archiving and Communication System server (PACS). All images were stored as Digital Imaging and Communications in Medicine (DICOM) format files. The digital archives system used was neaPACS (Neagen Ltd, Oulu, Finland), and the case selection systems, i.e., the Radiology Information System (RIS) used were neaRIS (Neagen Ltd, Oulu, Finland) and the ESKO Hospital information system (Oulu University Hospital, Oulu, Finland). The viewer used was an HTML4/5-based software application (neaLink, Neagen Ltd, Oulu, Finland.

Table 2. Technical specifications of two sets of four identical displays (original studies I, II, and III, modified Table 1).

Display Group	Manufacturer	Model	GSDF	Screen size (inches)	Screen type	Color	Resolution	Brightness (lx)	Error %	Brightness (lx)	Error %	Luminance (cd/m²)	Error %
CG 1	Fujitsu	P23T61PS	No	23.0	LED	Yes	1920 X 1080	510.2		16.2	1.22	206.2	
CG 2	Fujitsu	P23T61PS	No	23.0	LED	Yes	1920 X 1080	510.2	0.00	16.4		205.5	0.34
IPad 1	Apple	MD368KS	No	9.7	LED	Yes	2048 X 1536	513.7		16.2	0.61	344.8	
Ipad 2	Apple	MD368KS	No	9.7	LED	Yes	2048 X 1536	510.8	0.57	16.3		357.5	3.55
CG 1	Fujitsu	P23T61PS	Yes	23.0	LED	Yes	1920 X 1080	510.0		16.2	0.61	180.8	
CG 2	Fujitsu	P23T61PS	Yes	23.0	LED	Yes	1920 X 1080	508.5	0.22	16.3		179.2	0.45
6MP 1	Barco	MDCC6130DL	Yes	30.4	CCFL	Yes	3280 X 2048	509.5		16.3	1.88	391.7	
6MP 2	Barco	MDCC6130DL	Yes	30.4	CCFL	Yes	3280 X 2048	509.4	0.02	16.0		374.7	4.54

CG, Consumer grade color display; GSDF, Grayscale Standard Display Function; LED, Light Emitting Diode; CCFL, Cold Cathode Fluorescent Lamp; lx, lux; cd/m², candela per square meter.

4.2 Image evaluation

In all studies two sets of three to four identical displays were used for convenience and to save interpretation time. In Study I the displays were tablet (3^{rd} generation Apple iPad®), uncalibrated (i.e. γ 2.2) consumer grade and 6 MegaPixel (MP) displays. In Study II the displays were consumer grade displays with and without the digital imaging and communications in medicine (DICOM) part 14: grayscale standard display function (GSDF) calibration, a tablet (3^{rd} generation Apple iPad®), and a 6MP display. In Study III the displays were consumer grade displays with or without DICOM part 14: GSDF calibration, a tablet (3^{rd} generation Apple iPad®), and a 6MP display. Characteristics of the displays are summarized in Table 2.

A standard laptop PC (Lifebook S-761 VPro, Fujitsu, Tokyo, Japan, integrated graphics card: Esprimo C5731E, Tokyo, Japan) was connected to the consumer grade displays, and a power computer (Fujitsu Celsius R570, Fujitsu, graphics card: Barco 5200, Kortrijk, Belgium) to the 6MP displays. Prior to the study, comparable maximum luminance was set by adjustments of the displays between identical displays. Luminance was adjusted using a luminance meter (Unfors RaySafe Xi; Billdal; Sweden). The tablet was fixed on the table before adjusting the luminance. The DICOM calibration of all displays was in accordance with Section PS3.14 of the latest version of the standard (DICOM PS3.14 2014). Detailed specifications are given in Table 2.

4.3 Image analysis

In initial evaluation, altogether thirteen structures from the left side of the jaw were evaluated in the panoramic radiographs: the dentinoenamel junction from the first lower molar, the possible presence of dentinal caries from the first upper and lower primary and the first and second upper and lower permanent molars (proximal and occlusal surfaces) and periapical inflammatory lesions (widening of the periapical periodontal ligament space twice from normal or a radiolucent lesion) from the first and second upper and lower permanent molars, and the visibility of the border and possible pathological lesions in the maxillary sinus, such as thickening of mucous membrane, fluid level, or cysts.

Altogether fourteen structures were evaluated in bitewing radiographs: the dentinoenamel junction in the first lower permanent molar, the possible presence of enamel and dentinal caries in the first upper and lower primary molars and the first and second upper and lower permanent molars (proximal and occlusal surfaces), and the visibility of the cortical border of the alveolar crests.

In Study I and II, altogether seven structures were validated from the left side of the jaw: the dentinoenamel junction from the first lower molar, the possible presence of dentinal caries and periapical inflammatory lesions (widening of the periapical periodontal ligament space twice from normal or a radiolucent lesion) from the first upper and lower permanent molars, and the visibility of the border and possible pathological lesions in the maxillary sinus, such as thickening of mucous membrane, fluid level, or cysts (Figure 5). In Study III altogether ten structures were validated: the dentinoenamel junction in the first lower permanent molar, the possible presence of enamel and dentinal caries in the first and second upper and lower permanent molars, and the visibility of the cortical border of the alveolar crests (Figure 6). Both anatomical structures and pathology were chosen because they provided both low- and high-contrast details. The number of primary teeth was so low that they were not included in the present study.

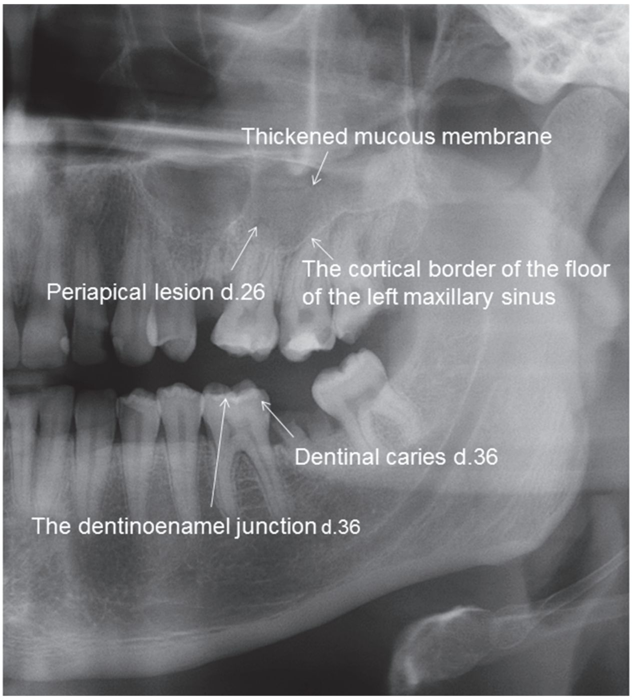

Fig. 5. Panoramic images from the left side of the jaw showing the structures under evaluation.

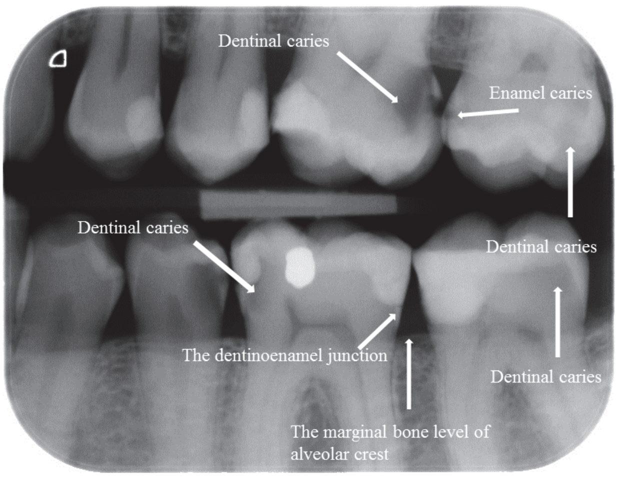

Fig. 6. Bitewing radiograph showing the structures under evaluation.

The radiographs were independently observed in random order by two observers: an oral and maxillofacial radiologist with eight years of experience (observer 1) and a resident in oral and maxillofacial radiology with two years of experience (observer 2). A five-point scaling system was used in Study I: 1= definitely not a finding, 2= probably not a finding, 3= unable to evaluate, 4= probably a finding, and 5= definitely a finding. In Study II and III rating was based on a three-point scaling system used in the analyses: 1= definitely not a finding, 2= uncertain, and 3= definitely a finding. In Study II the middle score would require further imaging, such as intraoral or even cone-beam computed tomography (CBCT).

The observers evaluated 60 radiographs (30 panoramic and 30 bitewing radiographs) in three evaluation sessions under bright and dim lighting conditions during which they were allowed to adjust the brightness, contrast and magnification of the radiographs in the viewing software. Prior to the study, the observers were familiarized with the software interface and the score sheets. To prevent potential learning bias of the observers, there was an interval of at least 2 weeks between successive evaluation sessions. The uncalibrated consumer grade display and tablet were evaluated during the first, the DICOM-calibrated consumer grade display during the second, and the 6MP display during the third evaluation. Evaluations were made under bright (510 lx) and dim (16 lx) lighting. There was a one-hour delay between the room illuminance settings. Evaluation time of one minute per image was allowed during which all different anatomical structures and pathology were assessed. Reading and viewing conditions are shown in Table 3.

A consensus between the two observers, which was considered as a reference, was made within each structure in all thirty panoramic and bitewing radiographs six months after the initial viewing. In the consensus reading session the 6MP display was used under ambient lighting of 16 lx (Table 2). Intraobserver agreement was determined by observer 1 by re-evaluating 15 panoramic and bitewing radiographs six months after the initial viewing using the 6MP display under ambient lighting of 16 lx (Table 2). Interobserver reliability was assessed.

Table 3. Reading and viewing conditions in panoramic and bitewing radiographs evaluation.

Sessions	Test	n	Viewing conditions	
			510 lx	16 lx
1	Reading 1	60	Consumer grade (ɣ 2.2)	
	Reading 2	60	Tablet (iPad)	
	Reading 3	60		Consumer grade (ɣ 2.2)
	Reading 4	60		Tablet (iPad)
2	Reading 5	60	Consumer grade (GSDF)	
	Reading 6	60		Consumer grade (GSDF)
3	Reading 7	60	6MP	
	Reading 8	60		6MP
	Total	480		

At least a two-week interval between evaluation sessions; lx, lux; GSDF, Grayscale Standard Display Function; MP, MegaPixels.

4.4 Statistical Methods

Statistical methods based on the book Statistical methods for rates and proportions (Fleiss *et al.* 2003). In Study I agreement between both observers and consensus was calculated as proportion of concordant ratings (i.e., exactly the same). The rating of dentinoenamel junction was dichotomized as *visible* or *unable to evaluate*. In order to evaluate the reliability of the ratings Cohen's kappa (κ) was calculated for dentinoenamel junction and linearly weighted kappa (κ_w) for dentinal caries and the presence of periapical lesions from upper and lower molars, and pathological lesions from maxillary sinus. Independent samples chi-square test was used to compare overall differences between the three displays and separately between the tablet and 6MP display. The linear association test was used to evaluate the linearity of agreement between the displays in observing pathological lesions.

In Study II agreement between both observers and consensus was calculated as a proportion of equivalent ratings. In order to evaluate the reliability of the ratings Cohen's kappa (κ) was calculated for dichotomized ratings of dentinoenamel junction and linearly weighted kappa (κ_w) and its 95% confidence interval for other structures. In order to compare the different displays (separately calibrated vs. uncalibrated consumer grade, calibrated consumer grade vs. 6MP and tablet vs. other displays) and lighting conditions (bright vs. dim) κ_w's were compared using z-scores. Only the images that were evaluated successfully in each display were selected for the comparison of displays, and the images that were evaluated successfully in bright and dim lighting within each display were selected for the comparison of lighting conditions.

In Study III agreement between the observers and consensus was calculated as a proportion of equivalent ratings for all structures. Additionally, the number and proportion of positive ratings (when positive in consensus) and negative ratings (when negative in consensus) were calculated. Rating of the dentinoenamel junction and cortical border of the alveolar bone was dichotomized as visible or unable to evaluate. In order to evaluate the reliability of the ratings linearly weighted kappa (κ_w) was calculated for enamel and dentinal caries. McNemar's test was used to compare the proportions of equivalent ratings separately in bright and dim lighting between 1) uncalibrated and DICOM-calibrated consumer grade displays; 2) DICOM-calibrated consumer grade and 6MP displays; 3) tablet and other displays; and 4) between bright and dim lighting for all displays. Only radiographs that were evaluated successfully in all displays were selected for the analyses.

In all studies kappa statistics were interpreted as follows: <0, poor (less than change); 0.00–0.20, slight; 0.21–0.40, fair; 0.41–0.60, moderate; 0.61–0.80, substantial; 0.81–0.99, almost perfect agreement (Landis JR & Koch GG 1977). P-values <0.05 were considered statistically significant. Intra-observer reliability was analyzed by calculating the κ_w between the 15 ratings that were done by observer 1 in the initial viewing and 6 months after the initial viewing. For inter-observer reliability, the viewings by observers 1 and 2 using the 6MP-display under dim lighting were used. IBM SPSS Statistics, version IBM SPSS Statistics 21 (IBM Corporation, Armonk, New York, USA) was used in Study I and 22.0 (IBM Corporation, Armonk, New York, USA) in Studies II and III for statistical analyses.

4.5 Personal involvement

The author of this thesis has participated in designing the studies, in acquisition, analysis, and interpretation of the data, and in drafting, revising and final approval of all the original articles of this thesis in collaboration with the research group. The literature searches were done by the author. The contribution of the author in all the original articles has been central. The author has written the first and final versions of the original articles.

5 Results

5.1 Effect of display type, DICOM-calibration and room illuminance in panoramic radiographs

The numbers of successful ratings for the observers under bright and dim lighting conditions on different displays are shown in Table 4. The number of successful ratings with different displays varied owing to problems with the network connection at the first evaluation and some coding typos.

Table 4. The numbers of successful ratings for observers 1 and 2 under bright and dim ambient lighting conditions in different displays in panoramic radiographs (original study II, modified Table 2).

Display	Observer 1		Observer 2	
	Bright	Dim	Bright	Dim
	n (%)	n (%)	n (%)	n (%)
Consumer grade	24 (80)	22 (73)	28 (93)	26 (87)
Tablet	17 (57)	25 (83)	24 (80)	27 (90)
DICOM-calibrated consumer grade	27 (90)	30 (100)	30 (100)	30 (100)
6MP	30 (100)	30 (100)	29 (97)	29 (97)

DICOM, Digital Imaging and Communication in Medicine; MP, Megapixels

5.1.1 Anatomical structures

Agreement and reliability of visibility of the dentinoenamel junction was achieved reasonably well with consumer grade, tablet and calibrated consumer grade displays in bright and dim lighting and with 6MP-display in bright lighting, whereas agreement was poor with 6MP display in dim lighting ($\kappa = 0.19$) by observer 1. Observer 2 performed better with the DICOM-calibrated display and 6MP display than with the consumer grade display or tablet (Table 5). The border of the left maxillary sinus was visible to both observers on all displays.

Table 5. Agreement and reliability of visibility of the dentinoenamel junction, separately for both observers and ambient lighting conditions on different displays in panoramic radiographs (original studies I and II, modified Tables 1 and 2).

Display	Observer 1				Observer 2			
	Bright		Dim		Bright		Dim	
	$\%_{Eqv}$	κ	$\%_{Eqv}$	κ	$\%_{Eqv}$	κ	$\%_{Eqv}$	κ
Consumer grade	79	0.54	77	0.51	68	0.39	69	0.40
Tablet	82	0.63	76	0.46	63	0.33	78	0.54
DICOM-calibrated Consumer grade	82	0.59	80	0.56	87	0.72	90	0.78
6MP	83	0.63	67	0.19	86	0.70	86	0.69

$\%_{Eqv}$, proportion of equivalent ratings; κ, Cohen`s kappa; DICOM, Digital Imaging and Communication in Medicine, MP, MegaPixels.

5.1.2 Pathological lesions, comparison between consumer grade display and tablet under bright lighting conditions compared to 6MP display under dim lighting conditions (I)

The observer performance of an experienced observer did not differ between different displays whereas the less experienced observer performed better with the 6MP display than with the consumer grade display or tablet.

The proportion of concordant findings between observer 1 and consensus did not differ statistically significantly between different displays (Table 6). However, agreement measured by κ_w was lower with the tablet than with consumer grade or 6MP displays in dentinal caries in upper and lower molars, and highest with the tablet as compared to consumer grade or 6MP displays in periapical lesions in upper molars. For pathological lesions in the maxillary sinus the agreement increased significantly from consumer grade to 6MP display (P=0.020 in linear association test). The proportion of concordant findings between observer 2 and consensus was higher with the 6MP display than consumer grade display or tablet in dentinal caries in upper and lower molars (P=0.027 and P=0.042, respectively), and periapical lesions in upper molars (P=0.005). In pathological lesions in the maxillary sinus the agreement was low with all displays.

Observer performance between tablet and 6MP display

For observer 1, detection of periapical lesions in upper molars did not differ significantly between tablet and 6MP displays. Observer 2 performed significantly worse on the tablet as compared to the 6MP display in detection of dentinal caries in lower molars ($p = 0.014$) and periapical lesions in upper molars ($P = 0.012$). Observer 2 performed non-significantly better with the tablet as compared to the 6MP display in other structures. (Table 6).

Table 6. Comparison of agreement between different displays in dentinal caries and periapical lesions in upper and lower molars and pathological lesions in the maxillary sinus, separately for both observers compared to the consensus rating in panoramic radiographs (original study I, table 3).

Pathology/Display	Observer 1				Obsever 2			
	$\%_{Eqv}$	κ_w (SE)	$P^{²}$	P^2	$\%_{Eqv}$	κ_w (SE)	P^1	P^2
Dentinal caries, upper molar			0.700	.500			0.027	0.057
Consumer grade	75.0	0.70 (0.18)			35.7	0.48 (0.13)		
Tablet	64.7	0.39 (0.22)			41.7	0.47 (0.14)		
6MP	76.7	0.71 (0.16)			69.0	0.53 (0.16)		
Dentinal caries, lower molar			0.381	0.252			**0.042**	0.014
Consumer grade	79.2	0.71 (0.18)			57.1	0.72 (0.15)		
Tablet	70.6	0.44 (0.21)			37.5	0.50 (0.14)		
6Mp	86.7	0.83 (0.17)			72.4	0.69 (0.17)		
Periapical lesion, upper molar			0.684	0.759			**0.005**	**0.**012
Consumer grade	50.0	0.28 (0.15)			25.0	0.28 (0.12)		
Tablet	64.7	0.64 (0.20)			25.0	0.16 (0.08)		
6MP	56.7	0,27 (0.15)			62.1	0.42 (0.13)		
Periapical lesion, lower molar			0.700	0.500			0.409	0.278
Consumer grade	75.0	0.67 (0.18)			50.0	0.29 (0.14)		
Tablet	64.7	0.62 (0.20)			50.0	0.37 (0.12)		
6MP	76.7	0.72 (0.17)			65.5	0.38 (0.13)		
Pathological lesion, maxillary sinus			0.062	0.345			0.869	0.772
Consumer grade	37.5	0.11 (0.09)			28.6	0.28 (0.10)		
Tablet	52.9	0.33 (0.17)			29.2	0.19 (0.09)		
6MP	70.0	0.43 (0.16)			34.5	0.19 (0.10)		

$\%_{Eqv}$, proportion of agreed ratings between the observer and consensus; κ_w, linearly weighted kappa; SE, standard error. Chi-square test, separately [1] between all displays and [2] between tablet and 6MP, MegaPixels. The p-values <0.05 are bolded

5.1.3 *Pathological lesions, comparison between DICOM-calibrated and uncalibrated consumer grade, tablet, and 6MP displays under bright and dim lighting conditions (II)*

The proportion of equivalent ratings with consensus differed between uncalibrated and DICOM-calibrated consumer grade displays in dentinal caries in lower molars in dim (P=0.021) and between DICOM-calibrated consumer grade and 6MP-display in bright (P=0.038) conditions for the more experienced observer. Significant differences were found between uncalibrated and DICOM-calibrated consumer grade displays in dentinal caries in bright (P=0.044) and in periapical lesions in upper molars in dim (P=0.008) conditions for the less experienced observer. The results are shown in Table 7.

Observer performance with tablet and other displays

The proportion of equivalent ratings with consensus differed between the tablet and DICOM-calibrated consumer grade display in dentinal caries in upper (P=0.043) and lower molars (P=0.06) in bright and in lower molars in dim (0.014) lighting conditions. The proportion of equivalent ratings with consensus differed between the tablet and 6MP display in dentinal caries in lower molars in bright (P=0.000) and dim (P=0.001) lighting conditions for the more experienced observer. Significant differences were found between the tablet and DICOM-calibrated consumer grade display in dentinal caries in lower molars in bright (P=0.034) conditions and in periapical lesions in upper molars (P=0.028) for the less experienced observer. The results are presented in Table 7.

Table 7. Comparison of agreement in dentinal caries and periapical lesion in upper and lower molars and pathological lesions in left maxillary sinus by different displays under ambient light of 510 lx and 16 lx, separately for observers 1 and 2 in panoramic radiographs (original study II, modified Table 4).

Pathology/ Display	Observer 1								Observer 2							
	Bright, n = 21				Dim, n = 22				Bright, n = 27				Dim, n= 25			
	$\%_{Eqv}$	κ_w (SE)	P[1]	P[2]	$\%_{Eqv}$	κ_w (SE)	P[1]	P[2]	$\%_{Eqv}$	κ_w (SE)	P[1]	P[2]	$\%_{Eqv}$	κ_w (SE)	P[1]	P[2]
Dentinal caries, upper molar																
Consumer grade	81.0	0.69 (0.14)		0.063	72.7	0.53 (0.16)		0.503	40.7	0.31 (0.09)		0.211	44.0	0.34 (0.10)		0.726
Tablet	66.7	0.33 (0.26)			66.7	0.42 (0.16)			50.0	0.44 (0.12)			45.8	0.29 (0.14)		
DICOM-calibrated consumer grade	81.0	0.71 (0.13)	0.841	**0.043**	63.6	0.33 (0.16)	0.201	0.542	66.7	0.53 (0.1)	**0.044**	0.465	52.0	0.42 (0.13)	0.453	0.332
6MP	76.2	0.60 (0.17)	0.452	0.194	72.7	0.55 (0.15)	0.153	0.424	63.0	0.69 (0.12)	0.520	0.936	68.0	0.53 (0.14)	0.453	0.099
Dentinal caries, lower molar																
Consumer grade	76.2	0.63 (0.14)		0.134	72.7	0.53 (0.15)		0.994	59.3	0.53 (0.10)		0.418	60.0	0.58 (0.11)		0.276
Tablet	66.7	0.35 (0.24)			66.7	0.52 (0.15)			50.0	0.44 (0.12)			70.8	0.69 (0.09)		
DICOM-calibrated consumer grade	81.0	0.80 (0.09)	0.158	**0.006**	81.8	0.82 (0.08)	**0.021**	**0.014**	77.8	0.69 (0.12)	0.130	**0.034**	72.0	0.63 (0.13)	0.674	0.603
6MP	95.2	0.95 (0.05)	**0.038**	**0.000**	90.9	0.91 (0.06)	0.201	**0.001**	55.6	0.47 (0.13)	0.064	0.865	80.0	0.72 (0.12)	0.490	0.803

Pathology/ Display	Observer 1								Observer 2							
	Bright, n = 21				Dim, n = 22				Bright, n = 27				Dim, n= 25			
	$\%_{Eqv}$	κ_w (SE)	P^1	P^2	$\%_{Eqv}$	κ_w (SE)	P^1	P^2	$\%_{Eqv}$	κ_w (SE)	P^1	P^2	$\%_{Eqv}$	κ_w (SE)	P^1	P^2
Periapical lesion, upper molar																
Consumer grade	57.1	0.18 (0.13)		0.057	72.7	0.54 (0.17)		0.810	40.7	0.21 (0.10)	0.719		36.0	<0.01 (0.12)		0.390
Tablet	58.3	0.43 (0.13)			77.8	40.9 (0.17)			40.9	0.17 (0.11)			41.7	0.09 (0.13)		
DICOM-calibrated consumer grade	52.4	0.22 (0.17)	0.782	0.177	59.1	0.32 (0.13)	0.131	0.285	59.3	0.22 (0.12)	0.907	0.660	60.0	0.31 (0.12)	**0.008**	**0.089**
6MP	71.4	0.50 (0.18)	0.116	.0.74	68.2	0.34 (0.19)	0.920	0.407	51.9	0.16 (0.11)	0.597	0.936	60.0	0.37 (0.12)	0.638	**0.028**
Periapical lesion, lower molar																
Consumer grade	71.4	0.54 (0.16)		0.332	77.3	0.57 (0.17)		0.289	51.9	0.32 (0.13)		0.928	60.0	0.39 (0.15)		0.834
Tablet	66.7	0.23 (0.15)			83.3	0.74 (0.14)			54.5	0.33 (0.11)			58.3	0.42 (0.12)		
DICOM-calibrated consumer grade	66.7	0.30 (0.17)	0.148	0.549	81.8	0.75 (0.11)	0.226	0.944	70.4	0.36 (0.16)	0.784	0.841	68.0	0.29 (0.16)	0.516	0.368
6MP	71.4	0.43 (0.21)	0.519	0.873	72.7	0.61 (0.14)	0.242	0.312	66.7	0.38 (0.15)	0.912	0.741	60.0	0.32 (0.16)	0.857	0.484

Pathology/ Display	Observer 1								Observer 2							
	Bright, n = 21				Dim, n = 22				Bright, n = 27				Dim, n= 25			
	$\%_{Eqv}$	κ_w (SE)	P^1	P^2	$\%_{Eqv}$	κ_w (SE)	P^1	P^2	$\%_{Eqv}$	κ_w (SE)	P^1	P^2	$\%_{Eqv}$	κ_w (SE)	P^1	P^2
Pathological lesion, maxillary sinus																
Consumer grade	33.3	0.08 (0.05)		0.116	54.5	0.28 (0.13)		0.849	29.6	0.25 (0.08)		0.187	32.0	0.29 (0.07)		0.271
Tablet	50.0	0.23 (0.15)			55.6	0.25 (0.15)			27.3	0.13 (0.09)			33.3	33.3 (0.07)		
DICOM-calibrated consumer grade	42.9	0.15 (0.09)	0.346	0.447	68.2	0.42 (0.17)	0.358	0.303	33.3	0.16 (0.06)	0.247	0.726	40.0	0.17 (0.08)	0.119	0.696
6Mp	47.6	0.20 (0.10)	0.604	0.764	77.3	0.53 (0.18)	0.522	0.091	40.7	0.21 (0.08)	0.554	0.407	36.0	0.15 (0.07)	0.734	0.342

$\%_{Eqv}$, proportion of equivalent ratings between the observer and consensus; κ_w, linearly weighted kappa, SE, standard error; 6MP, 6 MegaPixels; DICOM, Digital Imaging and Communication in Medicine. [a] Significance of z-score calculated between DICOM-calibrated and uncalibrated consumer grade display (upper p^1) and between 6MP and DICOM-calibrated consumer grade display (lower p^1). Tablet and other displays (p^2). The p-values <0.05 are bolded

5.1.4 Intra- and inter-observer reliability (I and II)

Intra-observer reliability was moderate at the dentinoenamel junction, almost perfect in upper and substantial in lower dentinal caries, fair in upper and substantial in lower periapical lesions, and moderate in pathological lesions in the maxillary sinus. Inter-observer reliability was slight at the dentinoenamel junction, fair in upper and substantial in lower dentinal caries, slight in upper and fair in lower periapical lesions, and fair in pathological lesions in the maxillary sinus. (Table 8). The inter-observer reliability in the border of the left maxillary sinus was evaluated as visible in all radiographs by both observers.

Table 8. Intra- and inter-observer reliability evaluated using 6MP-display under ambient light of 16 lx in panoramic radiographs (original study I, modified Table 4).

Anatomical structure/Pathology	Intra-obsever reliability		Inter-observer reliability	
	$\%_{Eqv}$	κ_w	$\%_{Eqv}$	κ_w
Dentinoenamel junction lower molar	86.7	0.60	69.0	0.13
Dentinal caries, upper molar	93.3	0.96	55.2	0.29
Dentinal caries, lower molar	86.7	0.70	72.4	0.63
Periapical lesion, upper molar	60.0	0.27	58.6	0.06
Periapical lesion, lower molar	86.7	0.65	69.0	0.38
Patholocical lesons, maxillary sinus	73.3	0.48	51.7	0.23

$\%_{Eqv}$; proportion of equivalent ratings; κ_w, linearly weighted kappa

5.2 Effect of display type, DICOM-calibration and room illuminance in bitewing radiographs (III)

5.2.1 Anatomical structures

The cortical border of alveolar crests was visible on all displays in both lighting conditions. The proportion of equivalent ratings with consensus in visibility of the dentinoenamel junction was lowest (65%) with consumer grade display in bright lighting and highest (95%) with 6MP display in both bright and dim lighting (Table 9). Out of 35 radiographs in which the dentinoenamel junction was rated as certainly visible in consensus, only 23 (66%) were rated as visible with uncalibrated consumer grade display, whereas 34 (97%) were rated as visible with 6MP (Table 9).

Table 9. The proportion of equivalent ratings in visibility of the dentinoenamel junction and numbers and proportions of positive ratings in different displays when rated a finding in consensus (n=35), separately in bright and dim lighting conditions in bitewing radiographs (original study III, modified Table 2).

Display	Bright		Dim	
	$\%_{Eqv.}$	$\#_{pos.}$ (%)	$\%_{Eqv.}$	$\#_{pos.}$%
Consumer grade	64.9	23 (65.7)	78.4	29 (82.9)
Tablet	83.8	29 (82.9)	81.8	29.(82.9)
DICOM-calibrated consumer grade	83.8	30 (85.7)	89.2	32 (91.4)
6MP	94.6	34 (97.1)	94.6	34 (97.1)

$\%_{Eqv.}$, proportion of equivalent ratings with consensus; $\#_{pos.}$(%), number of proportion of positive findings in the case of consensus finding; DICOM, Digital Imaging and Communications in Medicine; MP, MegaPixels.

5.2.2 Enamel and dentinal caries in upper and lower molars

The proportion of equivalent ratings between observers and consensus was statistically significantly lower in uncalibrated compared to DICOM-calibrated consumer grade display in enamel caries in upper and lower molars in bright conditions (P=0.013 and P=0.003, respectively). Likewise, the proportion of equivalent ratings between observers and consensus was statistically significantly lower in uncalibrated compared to DICOM-calibrated consumer grade display dentinal caries in lower molars in both bright (P=0.022) and dim (P=0.004) lighting conditions (Table 10). DICOM-calibrated consumer grade display had a lower proportion of equivalent ratings than 6MP display in dentinal caries in lower molars in bright lighting conditions (P=0.039).

The proportion of equivalent ratings was higher with tablet compared to the consumer grade display in enamel caries in upper molars (P=0.017) and lower compared to 6MP display in dentinal caries in lower molars (P=0.003) in bright lighting and in enamel caries in lower molars (P=0.012) in dim lighting (Table 10).

The uncalibrated consumer grade display worked poorly in detecting the corresponding findings (Table 11). Overall, none of the displays had high proportions of detecting dentinal caries.

Consumer grade display was significantly better in dim than in bright lighting conditions in detecting dentinal caries in the upper molars (P=0.035) (Table 10).

Table 10. Comparison of agreement between different displays in enamel and dentinal caries in upper (dd. 26,27) and lower (dd. 36,37) molars compared to the consensus rating, separately in bright and dim lighting conditions in bitewing radiographs (original study III, Table 3).

	Bright				Dim				
Pathology/Display n=74	$\%_{Eqv}$,	κ_w (SE)	p^1	p^2	$\%_{Eqv}$,	κ_w (SE)	p^1	p^2	p^3
Enamel caries, upper molars (d26 & d27)									
Tablet	77.0	0.61 (0.09)			70.3	0.48 (0.10)			0.23
Consumer grade	60.8	0.36 (0.09)	**0.013**	**0.017**	71.6	0.56 (0.09)	0.58	>0.99	0.08
DICOM-calibrated consumer grade	75.7	0.57 (0.09)	0.17	>0.99	75.7	0.52 (0.10)	0.34	0.45	>0.99
6MP	85.1	0.70 (0.08)		0.18	81.1	0.58 (0.10)		0.08	0.55
Enamel caries, lower molars (d36 & 37)									
Tablet	85.1	0.71 (0.09)			82.4	0.54 (0.11)			0.79
Consumer grade	75.7	0.49 (0.11)	**0.003**	0.09	79.7	0.53 (0.11)	0.11	0.77	0.51
DICOM-calibrated consumer grade	90.5	0.83 (0.07)	>0.99	0.39	87.8	0.73 (0.09)	0.18	0.42	0.63
6MP	91.9	0.77 (0.09)		0.23	94.6	0,.84 (0.08)		**0.012**	0.63
Dentinal caries, upper molars (d26 & d27)									
Tablet	73.0	0.42 (0.11)			79.7	0.54 (0.11)			0.27
Consumer grade	67.6	0.42 (0.09	0.79	0.48	79.7	0.62 (0.08)	0.73	>0.99	**0.035**
DICOM-calibrated consumer grade	70.3	0.43 (0.10)	0.42	0.80	77.0	0.54 (0.10)	>0.99	0.75	0.27
6MP	75.7	0.50 (0.10)		0.79	77.0	0.48 (0.10)		0.77	>0.99
Dentinal caries, lower molars (d36 & 37)									
Tablet	74.3	0.46 (0.11)			75.7	0.39 (0.11)			>0.99
Consumer grade	66.2	0.30 (0.10)	**0.022**	0.18	68.9	0.31 (0.11)	**0.004**	0.23	0.75
DICOM-calibrated consumer grade	78.4	0.56 (0.08)	**0.039**	0.58	81.1	0.50 (0.11)	>0.99	0.29	0.63
6Mp	89.2	0.75 (0.08)		**0.003**	82.4	0.54 (0.11)		0.23	0.13

$\%_{Eqv.}$,proportion of equivalent ratings; κ_w, lineary weighted kappa,; SE, standar error. Significancies from McNemar`s test, separately 1 between consumer grade and DICOM-calibrated consumer grade (upper-p-value), and DICOM-calibrated consumer grade and 6MP (lower p-value); 2 between tablet and other displays and 3 bright and dim lighting. DICOM, Digital Imaging and Communication in Medicine; MP, Megapixels. The p-values<0.05 are bolded

Table 11. The numbers and proportions of positive and negative findings on different displays in enamel and dentinal caries in upper (dd.26,27) and lower (dd. 36,37) molars in the case of a positive finding, respectively, in consensus, separately in bright and dim lighting conditions in bitewing radiographs (original study III, Table 4).

	Positive findings			Negative findings		
		Bright	Dim		Bright	Dim
Pathology/Display n=74	$\#_{Cons.}$	$\#_{Pos.}$(%)	$\#_{Pos.}$(%)	$\#_{Cons.}$	$\#_{Neg.}$(%)	$\#_{Neg.}$(%)
Enamel caries, upper molars (d26 & d27)	24			48		
Tablet		13 (54.2)	12 (50.0)		43 (89.6)	38 (79.2)
Consumer grade		7 (29.2)	12 (50.0)		36 (75.0)	39 (81.3)
DICOM-calibrated consumer grade		15 (62.5)	16 (66.7)		39 (81.3)	38 (79.2)
6MP		22 (91.7)	17 (70.8)		40 (83.3)	41 (85.4)
Enamel caries, lower molars (d36 & 37)	16			56		
Tablet		11 (68.8)	8 (50.0)		50 (89.3)	51 (91.1)
Consumer grade		7 (43.8)	7 (43.5)		47 (83.9)	50 (89.2)
DICOM-calibrated consumer grade		13 (81.3)	12 (75.0)		52 (92.9)	51 (91.1)
6MP		13 (81.3)	13 (81.3)		53 (94.6)	55 (98.2)
Dentinal caries, upper molars (d26 & d27)	9			60		
Tablet		5 (55.6)	6 (66.7)		46 (76.7)	50 (83.3)
Consumer grade		3 (33.3)	4 (44.4)		43 (71.7)	52 (86.7)
DICOM-calibrated consumer grade		4 (44.4)	5 (55.6)		45 (75.0)	50 (83.3)
6MP		7 (77.8)	5 (55.6)			50 (83.3)
Dentinal caries, lower molars (d36 & 37)	13			54	47 (87.0)	
Tablet		5 (38.5)	3 (23.1)		43 (79.6)	50 (92.6)
Consumer grade		2 (15.4)	3 (23.1)		50 (92.6)	45 (83.3)
DICOM-calibrated consumer grade		2(15.4)	4 (30.8)		50 (92.6)	51 (94.4)
6Mp		8 (61.5)	6 (46.2)		54 (100.0)	83 (98.1)

$\#_{Cons.}$, number of positive / negative findings (i.e. certainly a finding / not a finding) in consensus. $\#_{Pos.}$(%), number of proportion of positive findings when a finding in the consensus. $\#_{Neg.}$(%), number of proportion of negative findings when not a finding in the consensus.DICOM, Digital Imaging and Communications in Medicine; MP, MegaPixels.

5.2.3 Intra- and inter-observer reliability

The intra-observer reliability was fair in enamel caries in upper (κ_w = 0.36) and moderate in lower (κ_w = 0.44) molars, and substantial in upper and lower dentinal caries (κ_w = 0.66 and 0.64). On initial viewing, the dentinoenamel junction and the border of alveolar crests were evaluated as visible in all 15 radiographs while on re-viewing the dentinoenamel junction was once evaluated as an uncertain finding. The inter-observer reliability between the readers was fair in upper and substantial in lower enamel caries (κw = 0.29 and κw = 0.63, respectively), and moderate in upper and substantial in lower dentinal caries (κw = 0.46 and κw = 0.60, respectively). The dentinoenamel junction was evaluated as visible in all 28 radiographs by observer 1 and in 26 radiographs by observer 2, and the border of alveolar crests was evaluated as visible in all 28 radiographs by both observers. (Table 12).

Table 12. Intra- and inter-observer reliability evaluated using 6MP-display under ambient light of 16 lx in bitewing radiographs (original study III, modified Table 5).

Pathology	Intra-obsever reliability		Inter-observer reliability	
	$\%_{Eqv}$	κ_w	$\%_{Eqv}$	κ_w
Enamel caries, upper molars	86.7	0.36	66.1	0.29
Enamel caries, upper molars	90.0	0.44	87.5	0.63
Dentinal caries, upper molars	80.0	0.66	64.3	0.46
Dentinal caries, lower molars	93.3	0.64	85.7	0.60

$\%_{Eqv}$; proportion of equivalent ratings ratings; κ_w, linearly weighted kappa

6 Discussion

Radiography is an important tool in dental diagnostics. Many dental practitioners have switched from film to digital radiography. The quality of digital radiographs is dependent on each part in the imaging chain, and one of the weaker links in the process seems to be the display, along with the level of ambient light in the viewing room (Samei 2003). There is limited knowledge among dentists as to how observer performance is affected by type of display, lighting conditions or grayscale calibration (Hellèn-Halme *et al.* 2007, Odlum *et al.* 2012). Furthermore, clinical dentist practice requires a level of ambient light which is considerably higher than that recommended for viewing radiographs. The four displays tested in this thesis where chosen as a cross section of commercially available displays available for viewing digital images: a tablet (3^{rd} generation Apple iPad®) and an uncalibrated (i.e., γ 2.2) consumer grade display, a DICOM-calibrated consumer grade display and a 6 MegaPixel (MP) display as a high-resolution calibrated display in bright and dim lighting conditions. The purpose of this thesis was to evaluate the effect of display type, DICOM-calibration and room illuminance on panoramic and bitewing radiographs, and provide recommendations for type of display and acceptable illuminance levels in the room for interpretation of dental radiographs.

6.1 Visibility of high contrast structures

In the present thesis, high contrast structures such as the border of the maxillary sinus and alveolar crest were visible on all displays in both lighting conditions. In the visibility of the dentinoenamel junction in panoramic radiographs (Study I and II) the less experienced observer performed better with DICOM-calibrated consumer grade and 6MP displays than with an uncalibrated consumer grade display or tablet in both lighting conditions. For the more experienced observer the agreement was poor with 6MP display in dim lighting due to rating the structure more often as visible, i.e., definitely a finding, rather than uncertain compared to consensus. In bitewing radiographs, the visibility of the dentinoenamel junction was lowest with consumer grade and highest with 6MP display. These high-contrast structures are usually well-visualized on panoramic and bitewing radiographs (Baksi *et al.* 2010, Hausmann *et al.* 1991, Haring & Jensen 2000;433-434, Henriksson *et al.* 2008, Kaeppler *et al.* 2006, White & Pharoah 2009: 200-209, Vizzotto *et al.* 2011), which was also confirmed in this thesis. As reported previously, (Cederberg *et al.* 1999, Isildor *et al.* 2009), display resolution, luminance values, or display/matrix size of the images did not affect observer performance in the detection of anatomical structures in panoramic or bitewing radiographs with any of the displays studied.

6.2 Visibility of pathological lesions in panoramic radiographs

In this thesis, the permanent upper and lower molars were selected for evaluation. The panoramic radiograph is not a very effective substitute for intraoral radiograph in the detection of dentinal caries and periapical lesions. However, when patient positioning and head alignment are done correctly the central beam of the X-ray passes tangentially through the long axis of the tooth and the contact area in molar regions lesions, such as dentinal caries and periapical lesions, should be seen. Furthermore, panoramic radiograph has magnification, which improves the detection of carious and periapical lesions.

According to the author's knowledge, this is the first thesis investigating how DICOM-calibration and viewing conditions when using consumer grade display affect the diagnostic accuracy in panoramic radiographs. Previously, McIlgorm *et al.* (2013) and McIlgorm & McNulty (2015) concluded that Dicom-calibrated consumer grade display can improve image presentation of panoramic radiographs, and that Dicom-calibrated consumer grade display is equally preferred to medical grade display for an 8-bit image under 25 to 40 lux (McIlgorm *et al.* 2013, MgIlgorm & McNulty 2015). According to the present results, DICOM-calibration may improve observer performance in the detection of pathology in panoramic radiographs regardless of the room illuminance level. The DICOM-calibrated consumer grade display was better than the uncalibrated consumer grade and almost equal in detectability to the 6MP display in both lighting conditions. More specifically, the DICOM-calibrated consumer grade display was significantly better in identifying dentinal caries in upper molars (observer 2) under bright lighting, and in dentinal caries in lower molars (observer 1) and periapical lesions in upper molars (observer 2) under dim lighting compared to the uncalibrated consumer grade display. Compared to the DICOM-calibrated consumer grade display, observer 1 performed significantly better on the 6MP display in identifying dentinal caries in lower molars in bright lighting. Based on these findings it can be concluded that the DICOM-calibrated consumer grade display is adequate for the detection of pathology also in bright ambient light. On the other hand, in dental practice the room illuminance level is often higher than 510 lx, and thus it is recommended that the overall lighting level should be decreased when viewing radiographs in order to reduce reflections and improve the image contrast.

With new technology, potentially useful mobile devices and radiology applications, such as tablets, have become available. According to the U.S. Food and Drug Administration (FDA), tablets are not intended to replace full workstations and are indicated for use only when there is no access to a workstation (U.S. Food and Drug Administration 2013). Following the FDA report, tablets have come to be used in hospitals for different purposes, such as detection of cerebral infraction (Mc Laughlin *et al.* 2012, Yoshimura *et al.* 2013). Volonte *et al.* (2011) considered a tablet device a tool that is helpful for improving surgical performance as well as for teaching purposes (Volonte *et al.* 2011). Caffery *et al.* (2015) reviewed eleven studies evaluating tablets as compared to DICOM-calibrated displays, and they suggested that the diagnostic accuracy of radiological interpretation is not compromised by using the Apple iPad device for the modalities of CT, MRI and plain radiography (Caffery *et al.* 2015). Furthermore, they concluded that the Apple iPad® may be appropriate for an on-call radiologist to use for radiological interpretation. In Study I, it was concluded that compared to a more experienced oral and maxillofacial radiologist, a resident in oral and maxillofacial radiology with less experience in interpreting panoramic radiographs may be more dependent on a high-quality display used under dim viewing conditions to detect pathology in panoramic radiographs. More precisely, the less experienced observer showed significantly higher diagnostic ability with a 6MP display under dim lighting compared to a consumer grade display and a tablet under bright lighting in dentinal caries and periapical lesions in the first upper molar and in dentinal caries in the first lower molar. The performance of the more experienced observer was not significantly affected by the type of display. For the more experienced observer, however, the performance increased significantly from uncalibrated consumer grade display to 6MP display in pathological lesions in the maxillary sinus, which are known to be difficult to detect (Kim *et al.* 2011). Kim *et al.* (2011) found that less experienced observers showed lower diagnostic ability with a general color LCD display to detect inflammatory changes such as thickened mucosa on maxillary sinus floor in dark room conditions as compared to oral and maxillofacial radiologists with more than 15 years of experience (Kim *et al.* 2011).

In Study II the more experienced observer performed worse on the tablet than on the DICOM-calibrated consumer grade in both upper and low dentinal caries in bright lighting conditions and in dentinal caries in dim lighting conditions, and better on the 6MP display than tablet in dentinal caries in both lighting conditions. The less experienced observer performed worse on the tablet than on the DICOM-calibrated consumer grade display in dentinal caries in lower molars in bright lighting conditions and in periapical lesions in lower molars in dim lighting conditions. The overall results demonstrated that the tablet was worse than the DICOM-calibrated consumer grade and 6MP display for detection of dentinal caries in panoramic radiographs. It could be concluded that we need further studies on the clinical use of tablet devices in panoramic radiographs.

6.3 Visibility of enamel and dentinal caries in upper and lower molars in bitewing radiographs

In the current thesis, the DICOM-calibrated consumer grade display was significantly better than the uncalibrated consumer grade display and almost equal to medical displays for the detection of enamel and dentinal caries in bitewing radiographs. The tablet was slightly worse than medical displays and almost equal to the DICOM-calibrated consumer grade display in both lighting conditions. Overall, with consumer grade display the proportions of equivalent ratings were higher under dim than under bright lighting; statistically significantly for the interpretation of dentinal caries in upper molars.

The depth of approximal carious lesions displayed on bitewing radiographs seems to be used to determine cavitation risk and make treatment decisions in situations where the surface is clinically inaccessible. Earlier studies have reported that most dentists decide on restorative treatment when the lesion is restricted to the enamel in the bitewing radiograph (Espelid *et al.* 1985, Espeli 1986, Mileman & Espelid 1988, Nuttall &Pitts 1990). A minority of dentists considered the dentinoenamel junction as the threshold for the decision on restorative treatment Mileman & Espelid 1988, Nuttall &Pitts 1990), or that the lesion has penetrated less than one third to the dentin (Espelid *et al.* 1994, Mejàre *et al.* 1999). However, during the last decades very few dentists would restore lesions limited to enamel (Baraba *et al.* 2010,Tan *et al.* 2002, Tubert-Jeannin *et al.* 2004). Furthermore, when the lesion extends to the outer third/half of dentine in bitewing radiographs, operative treatment is recommended (Haak & Wicht 2013). Early detection of enamel carious lesions in radiographs is important as the probability of cavitation is low and the prospect of preventive treatment is good. The ability to detect carious lesions on dental radiographs depends on lesion depth: deeper lesions are easier to detect than relatively superficial lesions (Cederberg *et al.* 1998, Kang *et al.* 1998). Kang *et al.* (1998) also concluded that there is a difference in the contrast seen with artificial lesions compared with natural lesions. In the current thesis, to mimic clinical conditions lesion depth was not validated.

Pakkala *et al.* (2012) and Hellèn-Halme & Lith (2012) concluded that different displays and room ambient light levels did not affect the overall accuracy of intraoral radiographs in enamel caries detection (Pakkala *et al.* 2012, Hellèn-Halme & Lith 2012). In the current thesis, DICOM calibration significantly improved enamel caries detection as compared to uncalibrated display in bright lighting conditions. Tablet was significantly worse than 6MP display in detecting enamel caries in lower molars in dim lighting conditions, while consumer grade display was significantly worse than tablet in detecting enamel caries in upper molars in bright lighting conditions.

In the current thesis, the DICOM-calibrated consumer grade display was significantly better than consumer grade display for detection of dentinal caries in lower molars in both lighting conditions, whereas there were no significant differences between display type or lighting conditions for the detection of dentinal caries in upper molars. Previously, Hellèn-Halme *et al.* (2009) reported that there was no difference between bright and dim lighting conditions for the detection caries lesions in digital intraoral radiographs when the display was DICOM-calibrated (Hellèn-Halme *et al.* 2009). Recently, McIlgorm *et al.* (2013) and McIlgorm & McNulty (2015) found that a consumer grade display calibrated with DICOM can improve the presentation of dental radiological images, and a DICOM-calibrated consumer grade display is capable of displaying an image quality equal to medical display for 8-bit dental images (McIlgorum *et al.* 2013, McIlgorm & McNulty 2015).

Previously, the FDA Task Group agreed that a tablet was sufficient for diagnostic image interpretation under the recommended lighting conditions (under 40 lx) (U.S. Food and Drug Administration 2013). Araki *et al.* (2015) found the diagnostic accuracy of the Apple iPad Air® tablet to be lower than that of the 24-inch Dicom-calibrated medical display or the 23-inch consumer grade display calibrated according to AAPM TG-18 QC, especially in the detection of enamel caries, and there were no differences in the detection of dentinal caries (Araki *et al.* 2015). In their study, the tablet's resolution was higher, pixel pitch better, and luminance same or higher than that of other displays. Shintaku *et al.* (2012) reported that the 2nd generation Apple iPad® can effectively display images, comparably to the evaluated LCD-display, for the evaluation of approximal caries under bright light conditions. Furthermore, Shintaku *et al.* found that image size did not affect the ability to identify dental caries on the 9.7-inch tablet compared to the 24-inch LCD-display. Similar findings were made by Cederberg *et al.* (1999) and Isidor *et al.* (2009) (Ceberberg *et al.* 1999, Isidor *et al.* 2009). Cederberg *et al.* (1999) compared three medical-grade CRT displays and a laptop for the detection of interproximal caries. The authors did not detect a significant difference in diagnostic accuracy and luminance values, display/image size or resolution between these displays. Isidor *et al.* (2009) compared five LCD displays with different sizes and resolutions for the detection of caries. The authors did not detect statistically significant differences between the displays. In the current thesis, the resolution of the consumer grade display was lower than that of the tablet and the 6MP display or the matrix size of the displayed bitewing radiographs. The display resolution or matrix size of the images did not affect observer performance in the detection of caries in bitewing radiographs with any of the displays studied. Furthermore, the tablet was almost equal to the DICOM-calibrated display in detecting enamel and dentinal caries in bitewing radiographs also in bright lighting. Contrary to the FDA recommendation, the tablet was sufficient for diagnostic image interpretation under the recommended lighting conditions (U.S. Food and Drug Administration 2013).

6.4 Visibility of pathological lesions in upper and lower jaws in panoramic and bitewing radiographs

In the present thesis, the DICOM-calibrated consumer grade display was significantly better than the consumer grade display or tablet for the detection of dentinal caries in both lighting conditions in panoramic radiographs. Furthermore, the effect of DICOM-calibration was higher in dentinal caries in the lower than in the upper molars, especially in bright lighting conditions. The DICOM-calibrated consumer grade display was significantly better than the consumer grade display for detection of dentinal caries in lower molars in both lighting conditions, whereas there were no significant differences between display types or lighting conditions in the detection of dentinal caries in upper molars in bitewing radiographs. Furthermore, the tablet was slightly poorer than medical displays and almost equal to the DICOM-calibrated consumer grade display in both lighting conditions. Overall detection of dentinal caries in panoramic and bitewing radiographs was highest by the 6MP display. The ability to detect caries lesions on dental radiographs depends on lesion depth (Jacobsen *et al.* 2004, Young & Featherstone 2005). Some studies have concluded that diagnostic accuracy for the detection of very small carious lesions, is highly dependent on consumer grade display grayscale calibration and decreasing ambient light (Hellèn-Halme *et al.* 2008, Kutcher *et al.* 2006). In the present thesis, to mimic clinical conditions lesion grade was not validated. Deeper lesions are easier to detect than relatively superficial ones (Cederberg *et al.* 1998, Sansare *et al.* 20014), and this could be the reason why detection of dentinal caries in lower molars is more dependent on DICOM-calibrated or 6MP-displays.

One major factor that contributes to all observations is the human visual system. The human eye can see about 60 grayscales in the radiographs (White & Pharoah 2009: 231-232). To associate with differences in experience, training, or visual perception it seems that a very experienced radiologist can see approximately 150-170 shades of gray (Hellèn-Halme *et al.* 2013). Furthermore, with regard to visual perception, in low ambient light the rods are activated and small contrast differences on the display can be seen.

The less experienced observer performed worse on an uncalibrated display or tablet as compared to the DICOM-calibrated consumer grade or 6MP-display in periapical lesions in upper molars in dim lighting conditions, whereas there were no significant differences between display types or lighting conditions for detection of periapical lesion in lower molars. This could be the reason why very early periapical inflammatory lesions, i.e., widening of the periapical periodontal ligament space at the apex of the tooth twice from normal in the upper permanent molars, are difficult to detect against the air-filled maxillary sinus (Kim *et al.* 2011, White & Pharoah 2009: 200–209); furthermore, DICOM-calibration improves the detection of low contrast structures in radiographs (Fetterly *et al.* 2008).

6.5 Intra- and inter-observer reliability in panoramic and bitewing radiographs

In the present thesis, intra-observer reliability in anatomical structures was moderate in the detection of the dentinoenamel junction in panoramic radiographs, whereas the cortical border of the maxillary sinus was determined as definite. The dentinoenamel junction and the border of alveolar crests were evaluated as definite findings in all reevaluated 15 bitewing radiographs while on initial viewing the dentinoenamel junction was once evaluated as an uncertain finding. Intra-observer reliability in pathological lesions in panoramic radiographs was almost perfect in upper and substantial in lower molar dentinal caries, fair in upper and substantial in lower periapical lesions, and moderate in pathological lesions in the maxillary sinus. The intra-observer reliability was fair in enamel caries in upper and moderate in lower molars, and substantial in upper and lower dentinal caries. These findings are similar to those reported in earlier studies on intra-observer reliability in detection of anatomical structures and pathology in panoramic and intraoral radiographs (Baksi *et al.* 2010, Gröndahl *et al.* 1980, Hellèn-Halme *et al.* 2013, Kaeppler *et al.* 2006, Molander *et al.* 1993).

In any radiological study, the problem of inter-observer reliability is a recognized factor when observers have differing levels of training (Robinson 1997, Monnier-Cholley *et al.* 2004). It was also confirmed in this study. The inter-observer reliability in the anatomical structures was slight in the dentinoenamel junction in panoramic radiographs; whereas the cortical border of the maxillary sinus was determined as definite. In the dentinoenamel junction observer 1 used more often *visible*, whereas observer 2 used more often *unable to evaluate.* Inter-observer reliability in pathological lesion in panoramic radiographs varied from slight to substantial; and in bitewing radiographs from fair to substantial. Many studies have concluded that inter-observer agreement for carious lesions in the enamel is low (Hellèn-Halme *et al.* 2007, Wenzel 1998 ,Wenzel &Moystad 2010), which was also confirmed in this thesis. Overall inter-observer reliability results were similar as in earlier studies (Baksi *et al.* 2010, Kaeppler *et al.* 2006, Molander *et al.* 1993).

6.6 Strengths and limitations of the present thesis

In vitro studies have several limitations, and generalizations from such studies are for many reasons difficult to fit into clinical situations (Bader *et al.* 2002). Extracted teeth are not representative of a patient's dentition and radiographic examination is carried out under optimal conditions. A head-phantom could be used in studies of panoramic radiographs; however, a phantom represents an "average man", but it does not account for the many different individual variations in jaw and tooth morphology. Therefore, clinical studies are required. In the present clinical investigation, panoramic and bitewing radiographs from patients representative of the clinical setting were used. The selection criterion for the radiographs was that the structures to be evaluated had to be clearly visible.

The selection was made retrospectively by an oral and maxillofacial radiologist who did not participate in the evaluation.

Experienced observers were validated because previous studies have found that observer experience affects the overall accuracy in diagnosing dental radiographs (Gang *et al.* 2014, Kim *et al.* 2011, Tewary *et al.* 2011); this allowed focusing on displays without compromising diagnostic ability. Previously, significant differences in diagnostic performance between individual observers has been shown, and this has been proposed to associate with differences in experience, training, or visual perception, more experienced radiologist seeing more shades of gray (Hellèn-Halme 2013, Syriopoulus *et al.* 2000). For the present thesis, only two observers were available to participate in the observations: an oral and maxillofacial radiologist and a resident in oral and maxillofacial radiology. This is a limitation of the thesis and has an effect on the soundness of the conclusions. Nonetheless, both observers had relatively long experience in evaluating dental radiographs. Thus it could be concluded that if, for example, the experienced observer performed better with the DICOM-calibrated consumer grade display than the uncalibrated consumer grade display in the detection of dentinal caries in dental radiographs, this could be generalized to apply to general dentists. Furthermore, previously Hintze *et al.* (2003) demonstrated that the statistical power of a study on accuracy in caries detection is determined by the total number of observations made rather than the number of observers (Hintze *et al.* 2003). For this thesis data three surfaces from each molar were evaluated (total 720 surfaces); considering also the amount of observed radiographs, displays and luminance levels, it was considered sufficient to have two observers for the evaluation task.

The four displays tested in this thesis where chosen as a cross section of commercially available displays available for viewing digital images: a tablet (3rd generation Apple iPad®), an uncalibrated (i.e., γ 2.2) consumer grade display, a DICOM-calibrated consumer grade display and a 6 MegaPixel (MP) high-resolution calibrated display in bright and dim lighting conditions. The thesis aimed at comparing different displays instead of measuring the ability to make a correct diagnosis. Including all possible display technologies was a strength of the present thesis.

Only images that were evaluated successfully in each display were selected for the comparison of displays (Study II and III), and the images that were evaluated successfully in bright and dim lighting within each display were selected for the comparison of lighting conditions. Given the number of unsuccessful readings and technical problems, the thesis would have benefited from a larger number of images. The power of the thesis remains therefore limited.

There are some limitations pertaining to the present clinical investigation. First, instead of measuring the ability to make a correct diagnosis, a subjective method was used to determine the underlying differences in image quality between modalities. Second, a real golden standard method was not used; instead, consensus with two observers with the 6MP display was used as reference. The studies could have benefited from achieving a reference diagnosis from either histology in carious lesions and dentinoenamel junction in bitewing radiographs or using a CBCT in periapical lesions and floor and pathology in the maxillary sinus. The consensus reading was, however, conducted under presumably optimal conditions and after a period of six months from the original readings. Previously, histology has been used as golden standard in *in vitro* studies (Bader *et al.* 2002, Hellèn-Halme & Lith 2013, Wenzel 2006); however, such an approach is of limited value for a clinical setting. Third, ambient light of 510 lx, which in this thesis and the original studies represents bright ambient light, is typical in office environment. It may be that in the ambient light in dental practices is higher in the working environment as high as 1000 lx.

7 Conclusions

This thesis evaluated the effect of display type and room illuminance in viewing dental radiographs. The following conclusions can be drawn from the findings of the current thesis:

1. Anatomical structures are visible on all displays in both dim and bright lighting conditions in panoramic and bitewing radiographs.
2. DICOM-calibration may improve observer performance in the detection of pathology in panoramic radiographs regardless of the room illuminance level.
3. DICOM-calibration improves the detection of enamel and dentinal caries in bitewing radiographs, particularly in bright lighting conditions.
4. When viewing bitewing radiographs, a tablet display can perform almost equally compared to a DICOM-calibrated display in the detection of enamel and dentinal caries regardless of the room illuminance level.
5. When viewing panoramic and bitewing radiographs, the room illuminance should be significantly reduced.

8 Recommendations

A DICOM-calibrated consumer grade display can be recommended as a diagnostic tool with panoramic and bitewing radiographs. Furthermore, a DICOM-calibrated consumer grade display can be used instead of a medical display in dental practice without compromising the diagnostic quality, as it saves costs.

While it seems that there is no reason to limit the use of tablet devices in the interpretation of bitewing radiographs, the results were contradictory, particularly regarding interpretation of dentinal caries in panoramic radiographs. Thus it is recommended that tablet displays should be used with caution in dental radiography, and further research is needed on the clinical use of tablet devices.

In dental practice the room illuminance level is often high. It is recommended that the overall lighting level should be decreased in order to reduce reflections and improve the image contrast.

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Original publications

This thesis is based on the following articles, which are referred to in the next by their Roman numerals.

I Kallio-Pulkkinen S, Haapea M, Liukkonen E, Huumonen S, Tervonen O & Nieminen MT (2014) Comparison of consumer grade, tablet and 6MP-displays: Observer performance in detection of anatomical and pathological structures in panoramic radiographs. Oral Surg Oral Med Oral Pathol Oral Radiol Endod 118(1): 135-141.

II Kallio-Pulkkinen S, Haapea M, Liukkonen E, Huumonen S, Tervonen O & Nieminen MT (2015) Comparison between digital imaging and communication in medicine-calibrated and uncalibrated consumer grade and 6-MP displays under different lighting conditions in panoramic radiography. Dentomaxillofac Radiol 44(5): 20140365.

III Kallio-Pulkkinen S, Huumonen S, Haapea M, Liukkonen E, Sipola A, Tervonen O & Nieminen MT (2015) Effect of display type, DICOM-calibration and room illuminance in bitewing radiographs. Dentomaxillofac Radiol 45:20150129.

Original publications are not included in the electronic version of the dissertation.

1296. Timlin, Ulla (2015) Adolescent's adherence to treatment in psychiatric care

1297. Aatsinki, Sanna-Mari (2015) Regulation of hepatic glucose homeostasis and Cytochrome P450 enzymes by energy-sensing coactivator PGC-1α

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